PROGRAM FOR ADVANCED CONSTRUCTION TECHNOLOGY AT THE MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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This report summarizes the results of the Program for Advanced Construction Technology at MIT which was sponsored by the Department of Defense University Research. The research focused on advanced engineering materials, information technology, automation and robotics, remote sensing and methodologies related to technology assessment and management of construction. The report also describes: the results of a fellowship program for Ph.D. students; the impact on the graduate academic program; and the dissemination of information through various industry interaction activities.

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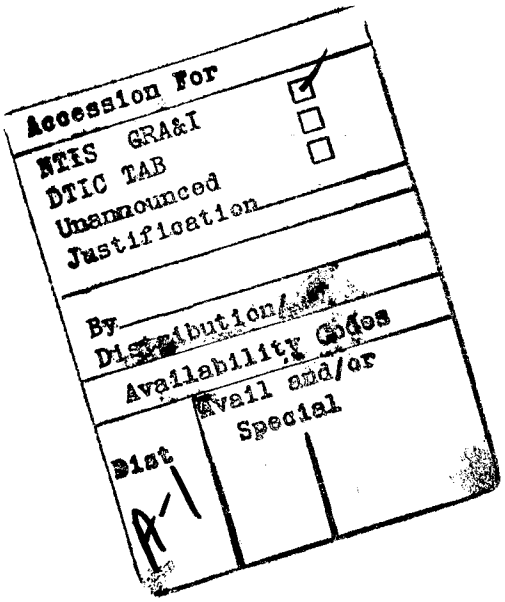
TABLE OF CONTENTS

TABLE OF CONTENTS



PREFACE

In 1986 the Massachusetts Institute of Technology proposed to establish a Program for Advanced Construction Technology in its Center for Construction Research and Education. The Program for Advanced Construction Technology sought to enhance the productivity, capabilities and competitiveness of the U.S. construction industry through programs of research, fellowship awards, equipment acquisition and information dissemination.

In research it proposed to focus on areas where technological advancements had a high potential for successful application to military construction. These areas included: advanced engineering materials, information technology, automation and robotics, remote sensing, and methodology related to technology assessment and management of construction.

The equipment acquisition program sought to provide a permanent and unique set of experimental facilities essential to the continued advancement of these technologies.

Various mechanisms were proposed for information dissemination and exchange of scientific knowledge, including an advisory board, publications distribution, meetings, conferences, and symposia, as well as continuing education seminars and exchange of faculty and personnel between the Center and industry.

The development of human resources with interest in and technical capabilities for continued technological advancement and its transfer was proposed to be accomplished through the Fellowship Program and through funding of research activities of M.I.T. faculty, research staff, and students. The Fellowship Program was anticipated to support 84 man years of graduate studies over the five year period. The research and other program activities of PACT was expected to support faculty, research staff and graduate students.

This report contains the results of PACT under the auspices of the University Research Initiatives, sponsored by the Department of Defense. The report is divided into four parts, consistent with initial broad set of objectives of URI. Part I focuses on institutionalization of the program; Part II deals with research activities of the program; Part III describes the academic program and its accomplishments; and Part IV describes information dissemination and industry interaction.

PART I

INSTITUTIONALIZATION OF PACT

Below is a broad overview of how the Center for Construction Research and Education (CCRE) was institutionalized within the framework and structure of M.I.T. and how the Program on Advanced Construction Technology, (PACT) sponsored by Army Research Office, Department of Defense, under its University Initiatives Program was tied into CCRE.

M.I.T. is a private academic institution primarily based on science and technology; and of the one billion dollars it receives annually, approximately $750 million is in the form of research funding from various governmental and industrial sponsoring agencies.

Structurally, M.I.T. is divided into five schools:

(1) **School of Architecture and Planning**
(2) **School of Engineering**
(3) **School of Humanities and Social Science**
(4) **Sloan School of Management, and**
(5) **School of Science**

In addition to the 21 academic departments which are housed within these five schools, there are more than 100 different interdepartmental laboratories and centers which facilitate work in fields which cross the lines of traditional disciplines. CCRE is an example of such a center.

The Institute makes available financial support to graduate students from a variety of sources and in several different forms, including: fellowships, scholarships, traineeships, teaching and research assistantships.

STRUCTURE OF THE CENTER FOR CONSTRUCTION RESEARCH AND EDUCATION

The Center for Construction Research and Education (CCRE) was established in February 1982 in the Department of Civil and Environmental Engineering, which is one of the eight departments within the School of Engineering. Its overall objectives and activities are directed by an Industry Advisory Board composed of five individuals from the following construction firms:

Mr. Jack T. Kavanagh, President
Badger America, Inc.

Mr. Paul F. Gorman, Chairman of the Board
Charles T. Main, Inc.

Mr. Louis G. Silano, Vice President
Parsons, Brinckerhoff, Quade & Douglas, Inc.

Mr. David I. Perini, Chairman
Perini Corporation

Mr. Harold J. Parmelee, President
Turner Construction Company

The Center does not employ research staff on a permanent basis other than a core of management staff, nor does it incur the financial cost associated with keeping permanent staff on its payroll. (See CCRE Organizational Chart). The Center has institutionalized itself along a cross-cutting theme - using faculty from other divisions, and departments of the University and using Adjunct Professors for its educational and research program focusing on the needs of the construction industry.

For example, it has supported faculty and research staff from the: Department of Civil and Environmental Engineering ; the Sloan School of Management; the Urban Studies and Planning Department; Department of Architecture; the Artificial Intelligence Lab; the Chemical Engineering Department; the Department of Electrical Engineering and Computer Sciences; the Department of Economics, Earth, Atmospheric and Planetary Sciences; the Energy Laboratory; the Arts and Media Laboratory; Humanities and Social Sciences; Intelligent Engineering Systems Lab; and the Material Sciences and Engineering Department. The URI sponsored PACT alone has supported 21 faculty members and 7 research staff members from these various departments.

The Director of CCRE has responsibility for overall supervision of the academic and research activities of the Center as well as coordination of the overall goals and objectives of CCRE.

The Deputy Director assists the Director in the overall management of the Center. In addition he has specific responsibilities for the academic program of CCRE, including the admission of graduate students to CCRE, development of academic courses, thesis supervision, and organization special lectures and seminars. He is responsible for coordinating and obtaining the participation of industry leaders in the education program; and he also acts as the Center's

liaison with the principal investigators of the research projects to provide technical supervision of research projects that are underway in the Center.

The Assistant Director for Administration is responsible for assisting the Director in overall management of the Center and specifically the day-to-day administration of the Center's activities as well as the Center's fiscal management. Technical administration of the individual research projects has been the responsibility of the faculty principal investigators; however strict financial monitoring mechanisms are in place to ensure compliance with contract regulations. In addition, she provides liaison of with other administrative entities at the Institute such as M.I.T's Patent Office, Technology Licensing Office, Office of Sponsored Programs, Property Office and Comptroller's Office.

The Center provides for Senior Lectureships to distinguished individuals from industry and government to participate in the research, education and/or industrial cooperation activities of the Center.

The goals of CCRE are:

- To provide a research environment conducive to development and application of innovative construction technologies and management principles.
- To offer graduate programs in construction engineering and management.
- To develop a culture within the construction industry which recognizes and supports greater industry involvement.
- To act as a facilitator and catalyst for research, educational and industry efforts to improve the contribution of the U.S. engineering and construction industry to the economy and society in general.

To achieve these goals, the CCRE conducts **education, research, and Industry Interaction programs** which address fundamental issues facing the construction industry in three broad dimensions: **resources** (capital, labor, and materials); **technology** (innovation, productivity, and advanced construction methods and systems); and **management** (at the industry, firm, and project levels).

Education

The Center's academic mission is implemented through the direction and administration of the graduate degree program in Construction Engineering and Management.

Research

The overall objectives of the research program at the Center are to discover, synthesize and apply knowledge needed to promote fundamental, long-term improvements in U.S. construction productivity and capability.

CCRE's research program was established on a multi-disciplinary basis to attract professionals from relevant science, engineering, and management backgrounds to the area of construction. The research program represents an integrated effort across topics, disciplines, and over time.

Industry Interaction

The Center has developed the "critical mass" needed to make a substantial contribution to industry. Through research and education, it provides for the trained manpower and capabilities needed to address industrial issues. A vital component of the Center's overall mission is to transfer the knowledge, experience, expertise and research results that we have achieved to industry.

The Center encourages exchange of personnel to interact with and work with respective counterparts on research projects. The primary mechanism for bringing research personnel to MIT is to invite them to join the Center for various periods of time as Senior Lecturers or Visiting Engineers.

The Center monitors all publications published under its collaborative programs such as research reports, technical reports, articles, and papers and student thesis. The availability of publications is publicized it its CCRE Newsletter which comes out three times a year.

Another mechanism, involves the M.I.T. Technology Licensing Office. The Technology Licensing Office at M.I.T. is the most active university patent and licensing office in the United States. Last year, 112 U.S. patents were issued to M.I.T. Over 50 license agreements were signed, many in conjunction with sponsored research agreements for further research in the field of the license.

From 1982 to 1986 the Center for Construction Research and Education operated at a level of approximately $650,000.00 a year. For the period 1987-1991 this figure increased to $10.1 million, or an average of $2.5 million/year, due, of course, to the URI awards to the Center for Construction Research and Education.

During the close out phase of PACT, The Center focused on building upon its accomplishments under the program and on fostering closer and more financially active ties with industry.

PROGRAM FOR ADVANCED CONSTRUCTION TECHNOLOGY (PACT)

In September 1986, CCRE was selected as one of the two Centers of Excellence in Advanced Construction Technology, (the University of Illinois being the other), under the Department of Defense University Research Initiatives Program. The PACT was incorporated into the administrative structure of CCRE (see PACT Organizational Chart). DOD grants and a research contract funded research projects, graduate fellowships, and equipment acquisitions in the Center for Construction Research and Education under its Program for Advanced Construction Technology. The overall goals of PACT are to discover, synthesize, and apply new knowledge needed for fundamental long-term improvements in the productivity and capability of the Nation's engineering and construction industry.

Scope of Activities

Within the first year the Center developed a general framework to carry out the mission and goals of PACT. This included:

1. **PACT Policy Committee** which consisted of:

   Professor Jerome Connor, Head of the Construction Facilities Division, Department of Civil Engineering

   Professor David Marks, Head of the Department of Civil Engineering

   Professor Fred Moavenzadeh, Director of the Program for Advanced Construction Technology and the Center for Construction Research and Education

   Professor Joseph M.Sussman, Director of the Center for Transportation Studies

   Mr. Charles H. Helliwell, Jr., Deputy Director of the Center for Construction Research and Education and PACT

Ms. Patricia A. Vargas, Assistant Director of the Center for Construction Research and Education and PACT

The PACT Policy Committee was concerned with the overall Program objectives and direction of the research. Its responsibilities included the following:

- Review Program activities to insure that they were consistent with the policies of the Army.
- Identify available resources and individuals within MIT who were interested in and qualified to participate in the Program.
- Review and comment on research proposals before final decisions were made regarding project approval and level of funding for each project.
- Discuss policy and administrative issues concerning the Program.
- Review the award of ARO Fellowships to Graduate Students
- Review equipment acquisition purchases.

2. **Army Research Office Review Committees** which were made up of individuals from various laboratories and centers of the Department of Defense. A sample listing of these individuals is provided in the following chart which represents the Review Panel sent to M.I.T. in October of 1990.

PACT REVIEW PANEL
OCTOBER 1990

Mr. Rich Lampo
Materials Engineer
Army Construction Engineering Research Laboratory
Box 4005
Champaign, IL 61824-4005

Dr. Eugene L. Marvin
Chief, Experimental Engineering Division
Cold Regions Research & Engineering Laboratory
Corps of Engineers
Hanover, NH 03755-1290

Dr. Dean Norman
Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Dr. Kevin O'Neil
Visiting Scientist at MIT
Room 26-305
(Cold Regions Lab) Replacing Eugene L. Marvin

Dr. L.R. Shaffer
Technical Director
Army Construction Engineering Research Laboratory
Box 4005
Champaign, IL 61824-4005

Dr. Robert E. Singleton
Engineering Sciences Division
Army Research Office
Box 12211
Research Triangle Park, NC 27709-2211

Dr. Robert Storer
Technical Director
Naval Civil Engineering Laboratory
Port Hueneme, CA 93043

Dr. Spencer T. Wu
Program Manager
Air Force Office of Scientific Research
Directorate of Aerospace Sciences
Bolling Air Force Base
Washington, D.C. 20332-6448

Dr. Joseph Walden
Building 115
Benet Weapons Laboratory
Watervliet Arsenal
Watervliet, NY 12189-4050

The Review Panel visited M.I.T. semi-annually to review the progress of the research projects and to advise M.I.T. if a change in direction was needed. In reviewing the projects, the Panel would concentrate on accomplishments to date and either suggest that M.I.T. continue the project as is, change the direction and scope of activities, or terminate the project.

3. Research Projects

Research was the primary vehicle for achieving the objectives of the Program, and it was used to provide a framework for organizing and implementing other Program activities.

After the selection of appropriate areas for research by the Program's Policy Committee, prospective principal investigators were identified from among M.I.T. faculty members, who then provided the Program with technical proposals.

The proposals included the following:

- Statement of objectives and scope of work.
- A description of the methodologies and analytic techniques to be employed.
- A description of project tasks and individual responsibilities.
- A description of needed facilities (equipment, computers).
- A work schedule and milestone chart, including any international or local travel anticipated.
- Biographical data on all project personnel (non-student).
- A budget for expenditures.
- A description of seminars, workshops, short courses which could potentially be conducted in connection with the research.

The projects were selected on the following basis:

- Qualifications of the individuals to perform the research, as evidenced by:
  - (a) Statement of prior work in the area;
  - (b) Analysis of resources (both new and existing) required to address the problem;
  - (c) Soundness of the proposed research methodologies; and
  - (d) Potential for significant results within one year.
- Utility of the anticipated project results.
- Contribution to the other activities planned with the framework of the Program: seminars, workshops, short courses, personnel exchanges.
- Potential for promoting an increased awareness of the capabilities of the Center in area of construction technology.

With the selection of the research projects, the principal investigators assumed responsibility for the following:

- Selection of project team members.

- Assignment of specific tasks.
- Maintaining liaison with the Program's administrative unit.
- Performance of the stated work, documentation of results, formulation of conclusions and recommendations.
- Planning for exchange of faculty, senior staff, and students, when appropriate.
- Organization of the project's workshops, seminars, and short courses.
- Budget control of financial resources allocated to the project by the Program.

All principal investigators were required to report the progress of their project on a semi-annual basis: first with an interim report covering the initial six months of the project's activity, and a final report covering the entire year. The reports contained the following information:

- A statement of project objectives, and the accomplishments of the project against these objectives.
- Linkages established to other organizations, industry firms and government laboratories.
- Information on workshops, seminars, and short coursees held in conjunction with the project.
- Reports and the publications which were available or in preparation.
- Potential for future research.

4. **Other Program Activities**

Within the context of the research projects, several other activities were organized in order to assist in dissemination of information to DOD and the construction industry. These include:

a. Contact with DOD Defense Centers and Labs

o Visits to:

- U.S. Army Construction Engineering Research Laboratory, Champaign, IL
- U.S. Department of the Navy, Naval

Civil Engineering Laboratory, Port Hueneme, CA

- U.S. Army, Secretary of the Army (Civil Works), Washington, D.C.
- Cold Regions Research and Engineering Laboratory, Hanover, NH
- Waterways Experiment Station, Vicksburg, MS
- U.S. Army Materials Technology Laboratory, Watertown, MA
- Oakridge National Research Laboratory (DOE)
- Laurence Berkeley Labs, San Francisco, CA

o Visits to M.I.T. from:

- URI/PACT Review Committees
- Readiness Technical Analysis Group
- Lieutenant General E.R. Heiberg, III to present Henderson Lecture on Foundation of Defense: Construction for National Security
- Dr. Robert Quattrone from CERL
- Honorable Jay R. Sculley, Asst. Secretary of the Army (Research, Development and Acquisition)
- Honorable Robert W. Page, Assistant Secretary of the Army (Civil Works) to present Henderson Lecture on Research and Development in the Construction Industry
- USA CERL personnel to M.I.T.

b. <u>Seminars and Conferences</u>

- The James A. Henderson Memorial Lectures
- CCRE Seminar Series
- The Richard L. Mullin Lecture
- Distinguished Speakers Series
- Roundtable Meetings
- Special Conferences

c. Publications

- CCRE Newsletter published three times a year
- Listing of CCRE Graduate Student Thesis Abstracts
- Research Papers

d. Patents and Licensing

o Advanced Engineering Materials/Systems

Lightweight Foam Composites (Timothy Tonyan and Lorna Gibson) M.I.T. Case 5523. Application Pending. This invention relates to lightweight composites for structural applications, particularly low density matrix composites characterized by sandwich beam micro-structures. This allows for low density cement foams to be used in the cores of sandwich panels. The advantages over polymers consist of: lower cost, higher stiffness, better fire resistance and familiarity to the construction industry.

o Automation and Robotics

Automated Shear Stud Welding System (Ziegler, Herschenfeld, Slocum). M.I.T. Case 5115. Pending.

Stud welding is highly repetitive and stressful on the worker; thus, it is a prime candidate for automation. A robotic device, called the "Studmaster", has been developed at M.I.T. which automates stud welding during construction of industrial buildings and can easily be adapted for use on bridge decks. The machine is controlled by a microcomputer, and utilizes a loading and welding mechanism which is actuated by three pneumatic cylinders and one mechanical relay. This mechanism is mounted on a small tracked vehicle which is manually indexed to each weld site by a human operator. Expected payback time for an industrially hardened version is estimated to be on the order of one to two years.

Implementation Plan

The major elements of the implementation plan for each year are presented below, in a general chronological ordering of the major tasks that were performed:

Month	Tasks
1	Policy Committee met and identified the exact scope of activities for each year. Research topics and potential principal investigators were selected.
2	Proposals prepared and submitted to the M.I.T. Policy Committee.
3	Proposals evaluated by Policy Committee, projects approved and funded.
3	Research project teams were organized and the work begun. Interim reports were asked to be submitted approximately halfway through the first period of project funding.
6	ARO Evaluation Team visits M.I.T. to review research proposals, recommend continuation, change in direction, or discontinuance.
11	The PACT Policy Committee and ARO Evaluation Team met to evaluate results and determine plans for the following years. Status Reports were prepared on the Program as a whole.
12	Annual Reports and Proposals for each of the remaining years submitted to ARO.

Financial Summary

In keeping with the overall Center's objectives, the initial proposal to ARO was divided into three components: **Fellowships, Research and Administration, and Equipment.** M.I.T submitted a proposal totalling $14,531,655.00, broken down as follows:

Equipment	$2,647,072.00	
Fellowships	$2,501,883.00	
Research/Admin.	$9,382,700.00	
Total:		**$14,531,655.00**
In Total MIT actually received		**$10,126,790.00**

	Year 1	Year 2	Year 3	Year 4	Year 5	Total
Equipment	$948,689.09	$ 339,341.68	$ 12,982.23	-	-	$1,301,013.00
Fellowships	$590,583.00	$ 351,800.00	$ 357,000.00	$ 509,100.00	$ 140,000	$1,948,483.00
Research	$594,482.90	$1,212,200.00	$1,420,130.00	$1,048,457.00	$1,526,309.00	$5,801,578.90
Administration	$171,502.10	$ 210,000.00	$ 231,108.00	$ 232,414.00	$ 230,691.00	$1,075,715.10
Total	$2,305,257.09	$2,113,341.68	$2,021,220.23	$1,789,971.00	$1,897,000.00	$10,126,790.00

Equipment represents:	**13%**
Fellowships	**19%**
Research	**58%**
Administration	**10%**
Total:	**100%**

*In addition to this figure, it should be noted that included in the Research total of $5,801,578.90 is the amount that is being used to support Graduate Research Assistantships on the various research projects. To date we have spent $1,690,530.

1. **Research and Administration**

For the Five Year Period 1987-1991 and the two and one half years close out phase, January 1992-June 1994, MIT was awarded a total of **$6,877,294** for research and administration.

	Research Projects	Administration	Total
Year I	$ 594,482.50	$ 171,502.10	$ 765,985.00
Year 2	$1,212,200.00	$ 210,000.00	$1,422,200.00
Year 3	$1,420,130.00	$ 231,108.00	$1,651,238.00
Year 4	$1,048,457.00	$ 232,414.00	$1,280,871.00
Year 5	$ 1,526.309.00	$ 230,691.00	$1,757,000.00
Totals	$5,801,578.00	$1,075,715.10	$6,877,294.00

2. **Fellowship Program**

MIT received **$1,948,483.00** for its Fellowship Program under PACT which has allocated support to 21 graduate students during the five year period and during the close out phase.

3. **Equipment Acquisition**

MIT received a total of **$1,301,013.00** for equipment to support its research activities. This money was distributed over a three year period as follows:

Year 1 (1987-1988)	$948,689
Year 2 (1988-1989)	$339,342
Year 3-5 (1989-1990)	$ 12,982 (Strictly for Maintenance

The equipment purchases for Year 1 were allocated to:

(1)	Materials Research	$316,000
(2)	Automation & Robotics	$276,000
(3)	Remote Sensing:	
	- General	$100,000
	- Hazardous Waste	$ 30,000
(4)	Computer Systems	
	- CAD, AI, Design	$144,000
	- MIS	$ 83,000

For Year 2 the funds were allocated to:

(1)	Materials Research	$149,000
(2)	Automation & Robotics	$ 50,000
(3)	Remote Sensing:	
	- Hazardous Waste	$ 43,000
	- Computer Systems	
	- CAD, AI, Design	$107,000
	- MIS	$ 5,000

For Year 3-5 the funds were allocated strictly for Maintenance $ 12,982

To summarize:

33%	Materials Research
25%	Automation and Robotics
13%	Remote Sensing
22%	CAD, AI, and Design; and
7%	MIS.
100%	Total

PART II

RESEARCH PROJECTS
FOR YEARS 1, 2, 3, 4, and 5
(1987-1991)

It is the premise of our work at the Center for Construction Research and Education (CCRE) that fundamental, high payoff, long-term research has been lacking on construction, and needs to be encouraged. Relying solely on incremental advances in technology is a weak strategy for regaining worldwide technological supremacy in construction. Worldwide leadership in construction needs breakthroughs in construction technology - quantum leaps of improvements in the ways in which construction is carried out.

Achieving technological leadership comes, of course, at a price. The research needed to produce a leap in technology is risky, takes time, is expensive, and requires a steady commitment by the concerned parties -owners, academics, the construction industry , and equipment and materials suppliers. Nevertheless, there are very strong reasons for arguing that the U.S. construction industry is uniquely situated to avail itself of this type of research, and that such a research program should be initiated, pursued and encouraged.

The conduct of research at a fundamental level in construction will require a program of scale, duration, and stability commensurate with the breadth and significance of the problem. To ensure that technological advances result in increased productivity and competitiveness, it is necessary to consider not only the technology itself, but also the inputs required for its use, and the industry setting surrounding its application. Furthermore, major advances in technology may fundamentally alter the way in which the industry is organized, financed, and operated; and these changes must be understood as well.

A model for major technological advance in construction is the mechanization of construction that occurred in highway construction as early as the 1920s. The significant improvements in productivity of highway construction which took place between 1920 and 1950 resulted from the conjunction of two major circumstances: one technologically driven, the other market driven. The technologically-driven trend was the growth of mechanization to replace animal-and human-powered equipment, leading not only to savings in labor, but also to a larger more efficient scale of operation. The market-driven trend was the growth of the U.S. highway program following World War I, a revolution in transportation accompanied by a significant industrial, organizational, and institutional change; e.g., the growth of the U.S. auto industry, the federal financing of road projects, and the concomitant establishment of state highway departments to supervise road work a nd related research.

A parallel situation exists today. There is a need for the U.S. construction industry to re-establish its technological pre-eminence and to regain its competitiveness worldwide. At the same

time, major new markets in environmental and infrastructure renewal have been identified for the construction industry - a market sufficiently large, dispersed, and diverse to guarantee significant payoffs on work done in research and development.

Similarly, developments in several areas of basic science have proceeded to the point where their resulting technologies are ready for adaptation and commercial exploitation in construction.

The Center's research program is also focused on those topics which have the greatest likelihood of success for innovative applications to construction, yet which the industry itself is not likely to fund on a large scale on its own.

CCRE's research program is established on a multi-disciplinary basis to attract professionals from relevant science, engineering, and management backgrounds to the area of construction. The research program represents an integrated effort across topics, disciplines and over time.

The research is organized in such a way that while it focuses on technological innovation, simultaneously it devotes considerable attention to the total context of construction. All research projects are either directed toward developing technology *per se,* or toward identifying technology needs, assessing technological impact, understanding the manner by which new technologies can be adapted and implemented in construction, and organizing and administering structures needed to expedite implementation of innovative technologies in the marketplace.

Recognizing the overall objectives of the Center for Construction Research and Education and its research thrust areas; namely, Technology, Technology Assessment, and Management, and recognizing the objectives of URI, research under PACT was initiated in automation and robotics; advanced materials, computers and information technology; remote sensing and diagnostics; innovation/diffusion; and productivity and competitiveness.

Exhibit A shows the distribution of PACT research projects and resources. Twenty-one faculty members have been supported by PACT and seven research staff members. A total of 26 projects over the five years have been funded, supporting 64 graduate students.

Exhibit A

Distribution of PACT Research Projects and Resources

	No. Projects	Project Years	No./Faculty & Research Staff	No. of Students	Student Years
Technology					
Automation & Robotics	2	4	2	9	15.0
Advanced Materials	7	21	8	16	31.0
Computers & Information Technology	3	8	5	7	17.0
Remote Sensing & Diagnostics	9	15	8	15	30.0
Technology Assessment					
Innovation/Diffusion	3	5	3	8	17.5
Productivity/ Competitiveness	2	3	2	9	11.5
Totals	26	56	28	64	122.0

First Year Projects

The first year of PACT research covered the period of January 15, 1987 to January 14, 1988. During that time the eight specific projects listed in Exhibit B were initiated. At the end of the year, three of the projects were either completed or terminated.

Second Year Projects

The second year of PACT research covers the period January 15, 1988 to January 14, 1989. However, research funds were not received until May, causing a delay in the selection and start of second year projects. A total of fourteen projects were initiated with second year research funds (See Exhibit C). Five of those projects were continuations of first year projects and the remaining nine were new projects involving faculty and research staff who participated in PACT for the first time.

Third Year Projects

The third year of PACT research covers the period January 15, 1989 to January 14, 1990. Fifteen projects were proposed for the third year. Thirteen were continuations of second year projects and two were new projects. These projects are identified in Exhibit D.

Fourth Year Projects

The fourth year of PACT research covers the period January 15, 1990 to January 14, 1991. Thirteen projects were funded in Year 4. Eight were continuations of third year projects and five are new projects. These projects are identified in Exhibit E.

Fifth Year Proposals

Fifth year PACT research projects total seven and are for the period January 15, 1991 to January 15, 1992. Five projects were continued from Year 4 and two new projects were added. These projects are listed in Exhibit F.

Research Project Descriptions

PACT research projects are described in Exhibit G.

CCRE/PACT Research Publications

A listing of all CCRE reports including PACT reports are shown in Exhibit H.

EXHIBIT B
LIST OF PACT PROJECTS
JANUARY 15, 1987 - JANUARY 14, 1988
FIRST YEAR FUNDING
(8 Projects)

TITLE OF PROJECT	PRINCIPAL INVESTIGATOR
Optimum Design Methods for Structural Sandwich Panels	Professor Lorna Gibson
Fiber Reinforced Light-Weight Structural Ceramics	Professor Victor Li
*Mechanics of Damage in Construction Materials	Professor S. Shyam-Sunder
*Advanced Ceramics in Construction	Mr. Michael J. Markow
The Role of Uncertainty in the Management of Infrastructure Facilities	Professor Sue McNeil
Design Methodology for Development of Automated Construction Machines: Blockbot	Professor Alex Slocum
*Assessment of In-Situ Conditions Using Wave Propagation Techniques	Dr. Kenneth R. Maser
Development of an Environment for Knowledge-Based Design	Professor Duvvuru Sriram

*Completed or Terminated at the End of Year 1.

EXHIBIT C
LIST OF PACT PROJECTS
JANUARY 15, 1988 - JANUARY 14, 1989
SECOND YEAR FUNDING
(14 Projects)

TITLE OF PROJECT	PRINCIPAL INVESTIGATOR
*Optimum Design Methods for Structural Sandwich Panels	Professor Lorna Gibson
*Fiber Reinforced Light-Weight Structural Ceramics for Construction	Professor Victor Li
*Adhesively Bonded Joints in Construction Polymers	Professor S. Shyam- Sunder
Scattering of Waves by Objects and Voids within Concrete Decks and Layered Pavements	Professor Eduardo Kausel
Algorithms for Automated Pavement Distress Detection	Professor Haris Koutsopoulos
Theory and Methods for Analyses of Infrastructure Performance and Maintenance Strategies	Professor Moshe Ben-Akiva
Soil Improvement and Composite Construction in Foundation Engineering	Professor Andrew Whittle
*Design Methodology for Development of Automated Construction Machines: Blockbot	Professor Alex Slocum
Computer-Aided Virtual Construction	Dr. John Williams and Professor Alex Pentland
*An Object-Oriented Programming Environment for Communication, Coordination and Control in Computer Design and Construction- Phase II	Professor Duvvuru Sriram
Quality in Design for Constructed Facilities	Professor Jerome Connor and Professor D. Sriram
Development of Methods for Advanced Construction Systems Exploration, Synthesis and Innovation	Professor Carl Peterson
Technology Evaluation to Improve the Effectiveness of Innovation	Professor Alice H. Amsden
Study of the Sources of Innovation in the Construction Industry and Exploration of Implications for Construction Industry Innovation Management	Professor Eric von Hippel

*Continued From Year One

EXHIBIT D
LIST OF PACT PROJECTS
JANUARY 15, 1989 - JANUARY 14, 1990
THIRD YEAR FUNDING
(15 Projects)

TITLE OF PROJECT	PRINCIPAL INVESTIGATOR
*Design Methods for Structural Sandwich Panels	Professor Lorna Gibson
*Fiber Reinforced Light-Weight Structural Ceramics for Construction	Professor Victor Li
*Adhesively Bonded Joints in Construction Polymers	Professor S. Shyam-Sunder
*Scattering of Waves by Objects and Voids within Concrete Decks and Layered Pavements	Professor Eduardo Kausel
*Algorithms for Automated Pavement Distress Detection	Professor Haris Koutsopoulos
*Theory and Methods for Analyses of Infrastructure Performance and Maintenance Strategies	Professor Moshe Ben-Akiva
*Soil Improvement and Composite Construction in Foundation Engineering	Professor Andrew Whittle
*Design Methodology for Development of Automated Construction Machines: Blockbot	Professor Alex Slocum
The Effect of As-Built Position Measurement Cost on the Automation of Construction Tasks	Dr. Laura Demsetz
*Computer-Aided Virtual Construction	Dr. John Williams and Professor Alex Pentland
*Quality in Design for Constructed Facilities	Professor Jerome Connor and Professor D. Sriram
*Development of Methods for Advanced Construction Systems Exploration, Synthesis and Innovation	Professor Carl Peterson
*Technology Evaluation to Improve the Effectiveness of Innovation	Professor Alice H. Amsden
*Study of the Sources of Innovation in the Construction Industry and Exploration of Implications for Construction Industry Innovation Management	Professor Eric von Hippel
Transfer of Technical Information in the Construction Industry	Professor Stephen Schrader

*Continued from Year two

EXHIBIT E
LIST OF PACT PROJECTS
JANUARY 15, 1990 - JANUARY 14, 1991
FOURTH YEAR FUNDING
(13 Projects)

TITLE OF PROJECT	PRINCIPAL INVESTIGATOR
*Design Methods for Structural Sandwich Panels	Professor Lorna Gibson
*Fiber Reinforced Structural Ceramics for Construction	Professor Victor Li and Christopher Leung
Adhesively Bonded Joints in Construction Polymers	Professor S. Shyam-Sunder
*Wave Propagation Techniques for Infrastructure Technology	Professor Eduardo Kausel
*Algorithms for Automated Pavement Distress Identification	Professor Haris Koutsopoulos
*Theory and Methods for Analyses of Infrastructure Performance and Maintenance Strategies	Professor Moshe Ben-Akiva
*Geosynthetic Reinforcement of Soil Masses	Professor Andrew Whittle
*Virtual Construction	Dr. John Williams and Professor Alex Pentland
*Design for Construction and Precision Design Scissor Link Deployable Structures	Professor Jerome Connor
Advanced Fiber-Reinforced Polymer Composite Materials in the Rehabilitation of Structures	Professor Thanasis Triantafillou
Assessment of Radar Technology for Concrete Deck Damage	Professor Daniele Veneziano
Assessment of Radar Technology for Determining Pavement Layers Thicknesses	Professor Moshe Livneh
An Alternative Conceptualization: Infrastructure Systems as Ill-Defined Systems	Dr. Frannie Humplick

* Continued from Year 3

EXHIBIT F
LIST OF PACT PROJECTS
JANUARY 15, 1991 - JANUARY 14, 1992
FIFTH YEAR FUNDING
(7 Projects)

TITLE OF PROJECT	PRINCIPAL INVESTIGATOR
*Core Materials for Structural Sandwich Panels	Professor Lorna J. Gibson
*Fiber-Reinforced Structural Ceramics for Construction	Dr. Christopher K.Y. Leung
Automated NDT of Concrete Using Sonic Methods	Professor Eduardo Kausel Professor Daniele Veneziano
*Automated Analysis of Pavement Distress Data	Professor Haris N. Koutsopoulos
*Geosynthetic Reinforcement of Soil Masses	Professor Andrew J. Whittle
*Virtual Construction	Professor Alex Pentland Professor John Williams
Advanced Fiber-Reinforced Polymer Composites as External Reinforcement of Concrete Structures: Bond Behavior With Emphasis on Long-Term Response	Professor Thanasis C. Triantafillou

*Continued from Year 4

EXHIBIT G
PACT RESEARCH PROJECT DESCRIPTIONS

I. TECHNOLOGY

A. AUTOMATION & ROBOTICS

1. Design Methodology for Development of Automated Construction Machines

Principal Investigator: **Alex Slocum**

Description of Project: The purpose of this project was to develop a design methodology for automating construction processes. Two robots, the Wallbot and Blockbot, were designed and laboratory prototypes built to help guide the development of the methodology. Based on their development, an assessment was made on common denominator mechanical, electrical, and sensor systems. One of the most critical technologies identified with respect to successful implementation was automating surveying techniques for real time control of construction machinery.

Researchers defined methodology for the efficient automation of construction processes. It addresses the decomposition of construction processes into specific tasks and the evaluation of current technology to determine whether a particular task should be automated or assigned to construction workers. Cooperation between architects, machine designers, building contractors, and materials suppliers is emphasized, along with the reduction in automated sensing requirements possible through use of information available from previously completed tasks whenever possible and reliance on humans when necessary.

The project involved a demonstration of the applicability of this design methodology to a typical building construction process. Characteristics deemed important in selecting the process included the following: complexity (the process should be complex enough to divide into tasks, yet reasonable to address in one to two years with limited student manpower), repeatability (the process should require fairly regular placement of materials), independence (automation should be possible

without disrupting the traditional building process), and size (the construction and testing of prototype machines should be feasible on a limited budget in restricted laboratory space).

Accomplishments/Products

Designing the Wallbot and Blockbot construction robots lend to the identification of the following common parameters: Mechanical systems: There is a need for lightweight kinematically designed linear servoactuator-bearing assemblies that can be assembled with other components in module form. Most sub-assembly components (e.g. bearings, ballscrews, and motors) exist as individual stock items, but there should be modular interface units that allow the easier assembly of these components into a design. This will facilitate economical design and fabrication of dedicated modular construction robots that would be easy to repair under harsh field conditions.

Electrical systems: Electrical system components are already available in the modular "plug-in" mode that is desired for mechanical components. Technology in this area is thus entirely adequate.

Sensor systems: Conventional surveying systems are far too slow, inaccurate, or require too much human input to make them useful as sensor feedback elements for real time control of construction robots. To date, the only surveying tool that is useful for construction automation is the rotating laser beacon and light mast that is often used to control blade height during precision grading operations. Other sensors such as tilt meters, theodolites and EDMs are either too slow, too inaccurate, or require too much human effort to be effective. The attainment of a fully active Global positioning System will help layout location of system, but will not be fast enough to achieve the 0.001 second update times required to facilitate real time control of robots. Thus research is needed in the area of fast, automated, accurate sensors for angle and distance measurement with part per million accuracies.

Overall conclusions included the following:

- Construction robots can be designed to effectively increase productivity and quality of specific construction tasks.

- General purpose construction robots (e.g. robots which emulate a human worker) are neither technologically or economically feasible, and will not be for the foreseeable future.

- Because only dedicated machines are technologically or economically feasible, the technology for designing dedicated construction robots is well known by experienced designers of machine tools and robots.

- The principal research endeavors needed to advance the state-of-the-art of construction robots are:

  a. Identification of which processes to automate. This requires a thorough detailed analysis of the construction process on a case by case basis for all types of construction processes. Only then can the go-ahead for the design of a specific robot be given.

  b. Development of advanced angle and distance measuring sensors with order of magnitude greater accuracy and speed than are presently available. Because sensors are so expensive, the number required needs to be minimized in reduce cost, but more importantly, to reduce the chances of damage on-site. Maximizing the autonomy of any given construction robot requires an increase in sensor accuracy so the robot can perform for a longer period before a sensor is needed to pick up where another sensor's accuracy is left off. Research in this area could overlap with the Strategic Defense Initiative program.

In the third year of the project a prototype machine was designed and fabricated for the welding of shear studs on buildings on bridge decks or on other structural steel members to be encased in concrete. This work

is not only highly repetitive but also physically stressful on construction workers. The stud and ferrule feeding mechanisms were extensively tested in the lab without failure. An initial field test indicated that while the machine is likely to be practical, there is still considerable development work to be done before a useful and productive machine can be manufactured. Illinois Tool Works, Inc. took out an option agreement in order to evaluate the technology to determine the extent of interest in commercialization of the machine. The company decided not to proceed with further development.

Publications

Slocum, A.H., L. Demsetz, D. Levy, B. Schena, and A. Ziegler, "Construction Automation Research at the Massachusetts Institute of Technology", presented at the Third International Symposium on Construction Robotics, June 22-24, 1987, Haifa, Israel.

Slocum, Alexander H., L. Demsetz, D. Levy, and B. Schena, "Design Methodology for Automated Construction Machines", CCRE/PACT Report #87-20, 1987.

Slocum, Alexander H., and A.Ziegler, "An Automated Shear Stud Welding System", Robotics and Autonomous Systems 6 (1990) 367-382.

Research Assistants/Theses

Levy, David, "Studbot: A Construction Robot for the Automated Assembly of Steel-Stud Partition Walls."
SMME 9/87

Schena, Bruce, "Design Methodology for Large Work Volume Robotic Manipulators: Theory and Application."
SMME 9/87

Ziegler, Andrew, "The Design and Fabrication of an Automated Shear Stud Welding System."
SMCE 8/88

Demsetz, Laura, "Task Identification and Machine Design for Construction Automation."
Ph.D. 5/89

Heatzig, Eric, "Design and Implementation of a High-Speed DSP Motion Controller."
SMCE 5/89

2. Effect of As-Built Position Measurement Cost on the Automation of Construction Tasks

Principal Investigator: **Laura Demsetz**

Description of Project: Uncertainty about the position of previously installed components presents an obstacle to the on-site automation of construction tasks. This project examines the ways in which this obstacle can be overcome, addressing in particular the tradeoff between:

(i) reducing uncertainty through measurement and

(ii) reducing the impact of uncertainty through the addition of compensating features in automated equipment. The approach to the project includes a survey of current measurement technology to determine cost of function of range, speed, accuracy; determination of position uncertainty for sample construction task (drywall installation); and evaluation of the impact of uncertainty on automation.

Accomplishments

The research completed the survey of measurement technology and the estimates of position uncertainty in drywall installation.

Publications

"Task Identification for Construction Automation" in Proceedings of Sixth International Symposium on Automation and Robotics in Construction, San Francisco, June 1989, pp. 95-102.

B. ADVANCED MATERIALS & SYSTEMS

1. Optimum Design of Structural Sandwich Panels/Core Materials for Structural Sandwich Panels

Principal Investigator: **Lorna Gibson**

Description of Project: In this project we studied the design of foam core sandwich panels. The first phase of the project examined the minimum weight design of foam core panels. Continuing

from a previous CREL project on minimum weight design of a foam core panel for a given stiffness, in the PACT project, we analyzed the minimum weight design of a sandwich panel for a given strength, and then a minimum weight design of a sandwich beam or plate which combines stiffness and strength. A software package for use on an IBM PC was developed to perform the analysis. In the second phase of the project we studied creep of polymer foams and sandwich panels with polymer foam cores; both analysis and mechanical testing were performed. In the third phase of the project we have been interested in the use of non-polymeric foam cores for structural sandwich panels, for example, cement foams. The fracture toughness of a brittle honeycomb and a brittle foam was analyzed, accounting for a Weibull distribution of strut strengths. The results indicated that control of the cell size could be use to improve the fracture toughness of brittle foams. In the last year of the project we have also been investigating the use of composite foams for the cores of structural sandwich panels.

Accomplishments/Products

- Minimum weight design of a sandwich beam or plate for a given combination of stiffness and strength - analysis and software package.
- Analysis and test results of creep of polymer foams.
- Analysis and test results of creep of sandwich panels with polymer foam cores.
- Review of behavior of fibre reinforced polymer foams.
- Analysis and test results of fracture toughness of brittle cellular materials (honeycombs and foams).
- Analysis and test results for moduli of hollow sphere/matrix composite cellular materials.

Publications

Triantafillou, T.C. and Gibson L. J. "Debonding in Foam Core Sandwich Panels", Materials and Structures, 1989, 22, 64-69

Gibson, Lorna J., "The Use of Models for Foam Core Behaviour in the Desing of Sandwich Panels" Sandwich Constructions 1, Proceedings of the first International conference on Sandwich Constructions, 19-21 June, 1989, Stockholm, Sweden.

Huang, J.S. and Gibson, L.J. (1990) "Creep of Sandwich Beams with Polymer Foam Cores" Journal of Materials in Civil Engineering 2, 171-182.

Huang, J.S. and Gibson, L.J. (1991) "Creep of Polymer Foams" Journal of Materials Science 26, 637-647.

Huang, J.S. and Gibson, L.J. (1991) "Fracture Toughness of Brittle Honeycombs" Acta Metallurgica et Materialia 39, 1617-1626.

Huang, J.S. and Gibson, L.J. (1991) "Fracture Toughness of Brittle Foams" Acta Metallurgica et Materialia 39, 1627-1636.

Huang, J.S. and Gibson, L.J. "Optimum Cell Size and Density of Brittle Foams for a Given Compressive Strength and Fracture Toughness" submitted to Journal of Material Science Letters 12 (1993) 602-604.

Tonyan, T.D. and Gibson L.J. "Structure and Mechanics of Cement Foams" Journal of Materials Science 27 (1992) 6371-6378.

Tonyan, T.D. and Gibson L.J. " Strengthening of Cement Foams" Journal of Materials Science 27 (1992) 6379-6366.

Huang, J.S. and Gibson, L.J. "Materials and Cross-Sectional Shapes for Bending Stiffness" Materials Science and Engineering A163 (1993) 51-59.

Huang, J.S. and Gibson, L.J. "Elastic Moduli of a Composite of Hollow Spheres in a Matrix" submitted to the Journal of the Mechanics and Physics of Solids Vol. 41, No. 1, pp 55-75, 1993

Research Assistants/Theses

Huang, J.S. "Foam Core Materials for Structural Sandwich Panels
Ph.D.Thesis May, 1991.
Current Status: Assistant Professor, Department of Civil Engineering, National Cheng Kung University, Tainan, Taiwan.

Kucirka, Mark, "Analysis and Design of Sandwich Panel Residential Roof Systems"
SMCE 6/89

Tonyan, T.D. "Mechanical Behavior of Cementitious Foams"Ph.D. Thesis, February, 1991 (PACT Fellow).
Current Status: Construction Manager, Davis International, San Francisco.

Triantifillou, Thanasis, "Failure Mode Maps and Minimum Weight Design for Structural Sandwich Beams with Rigid Foam Cores."
SMCE 2/87, and
"Multi-Axial Failure Criteria for Cellular Materials."
Ph.D. 6/89

2. Fiber-Reinforced Structural Ceramics for Construction

Principal Investigator: **Christopher K.Y. Leung**

Description of Project: Short fiber reinforced ceramics has been identified as a group of material with potential applications as advanced construction materials. Quantitative guidelines for the design and optimization of such materials are, however, unavailable. The objective of the project is therefore to develop micromechanical models to relate macroscopic behavior of composites (such as strength, toughness and reliability) to micro-properties (properties of fiber, matrix and fiber/matric interface) as well as residual stresses. With such models, the selection of material systems to be developed can be greatly facilitated. Moreover, with the development of techniques for controlling micro-properties, the models can serve as guidelines for optimization of composite properties.

Accomplishments/Products

The development of micromechanical models involve two steps: modelling of micromechanisms to obtain the relationship between crack bridging stresses and crack opening; and the analysis of the propagation of a bridged crack. During the last few years, our research has contributed to both these areas. Specific achievements include:

(i) Two-way bonding model of the fiber debonding process-our analysis revealed the possibility of two-way bonding (i.e., the occurrence of debonding from both the pulled and embedded ends of the fiber when it is pulled at one end), a phenomenon that has been neglected in traditional debonding models. We showed further that for composites with relatively high volume fraction of stiff fibers (such as ceramic composites), the use of traditional one-way debonding theories will lead to overestimation of both composite strength and composite reliability. The two-way debonding models therefore expand the range of applicability of existing debonding models to more general cases.

In composites with interfacial behavior dominated by friction, a strength-based debonding criterion (i.e., debonding occurs once a critical interfacial strength is reached) should be used. For composites with interfacial behavior governed by interfacial bonding, a fracture-based criterion (i.e., debonding occurs if the energy release associated with debonding is greater than a critical interfacial fracture energy) is desirable. Two-way debonding theories have been developed with both the strength-based and fracture-based approaches, thus accounting for both types of composite interfacial behavior.

(ii) Modelling of Fiber Bending/Matrix Spalling Mechanism-as crack opening increases, fibers that are not perpendicular to the crack plane will be bent as well as pulled. When fibers are bent onto the matrix, spalling may occur. The bending of oblique fibers across a crack and the corresponding crack bridging stresses have been analyzed by treating the fiber as a beam bent on an elastic foundation with variable stiffness and the possibility of spalling. Foundation properties are obtained from a finite element analysis. The prediction of crack bridging force for inclined fibers compared favorably with experimental results. With this model, the effect of various micro-parameters on crack bridging stress (and hence composite behavior are investigated and guidelines for the design of composites with high strength and toughness can be deduced.

The model was first developed for brittle fibers which may break due to a combination of stretching and bending but is recently extended to the case with ductile fibers.

(iii) Theoretical prediction of tensile behavior of composites - a methodology for the determination of complete tensile behavior of composites was developed and demonstrated for the relatively simple cases of aligned fibers and randomly distributed flexible fibers. For such simple cases, analytical solutions of the

fracture analysis reveal that composite behavior is governed by a dimensionless parameter which is a function of the micro-properties. By choosing the micro-properties in such a way to reduce this parameter below a certain critical value, the composite will behave as a pseudo-ductile material with high material reliability. Our work therefore provides a guideline for the design of pseudo-ductile and reliable composites.

In summary, through the research work on theoretical modelling supported by the ARO, we now have the capacity to relate the strength, toughness, reliability and pseudo-ductility of randomly distributed ductile or brittle fiber reinforced brittle matrix composites to the micro-properties of the composite. While our models are developed for composites with brittle matrix (such as glasses and ceramics), they can be applied to quasi-brittle matrix composites (such as fiber reinforced concrete and mortar) with very slight modifications.

Publications

Li, V.C. & Leung, C.K.Y., "Ceramics for Construction", Construction and Building Materials, Vol. 2, No. 2, pp. 59-68 (1988).

Leung, C.K.Y. & Li, V.C., "First-Cracking Strength of Short-Fiber Reinforced Ceramics", Ceramics Engineering & Science Proceedings, Vol. 10, No. 9-10, pp. 1164-1178 (1989).

Leung, C.K.Y. & Li, V.D., "Applications of a Two-Way Debonding Theory to Short-fiber Composites", Composites, Vol. 21, No. 4, pp. 305-317 (1990).

Leung, C.K.Y. & Li, V.C., "Strength-Based and Fracture-Based Approaches in the Analysis of Fiber Debonding", Journal of Materials Science Letters, Vol.9, pp. 1140-1142 (1990).

Leung, C.K.Y. & Li, V.D., "A New Strength-Based Theory for the Debonding of Discontinuous Fibers in an Elastic Matrix", accepted by Journal of Materials Science 26 (1991) 5996-6010

Leung, C.K.Y. & Li, V.C., "Effects of Fiber Inclination on Crack Bridging Stresses in Brittle Matrix Composites", accepted by Journal of the Mechanics and Physics of Solids Vol. 40 No. 6 pp 1333-1362 (1992)

Li, V.C. & Leung, C.K.Y., "Steady-State and Multiple Cracking of Short Random Fiber Composites", submitted to ASCE Journal of Engineering Mechanics Vol. 118, No. 11, November 1992

Leung, C.K.Y., "A Fracture-Based Two-Way Debonding Model for Discontinuous Fibers in an Elastic Matrix", submitted to ASCE Journal of Engineering Mechanics (1991).

Research Assistants/Theses

Leung, Christopher K., Ph.D. Thesis:-Micromechanical Modelling of Short Fiber Reinforced Ceramics, May 1990
Current Status: Assistant Professor at Department of Civil and Environmental Engineering, MIT.

Chi, Jeff C., M.Sc.Thesis:-Micromechanical Modelling of Ductile Fiber Reinforced Ceramics, February 1992.

3. Mechanics of Damage in Construction Materials

Principal Investigator: **Dr. S. Shyam-Sunder**

Description of Project: The overall goal of this project was to investigate the mechanics of damage in advanced construction materials: fiber-reinforced plastics, ceramics and ice. This was accomplished through the development of predictive models for describing damage processes during deformation; particularly, first crack formation and distributed cracking under uniaxial and triaxial loading. Experimental procedures and equipment were designed and developed for validation of the theory by monitoring acoustic emissions.

Accomplishments/Products

The following was accomplished during this one year project:

1. Review of the literature on: (a) first cracking in structural plastics and ice, (b) fracture in ceramic materials and ice, and (c) quantitative acoustic emission theory.

2. Development of technical specifications and design of a customized high-capacity loading frame and triaxial cell for mechanical testing of advanced construction materials in the ductile-to-brittle transition range of strain rates under both uniaxial and triaxial loading. The system can maintain a pre-specified ratio of axial to confining pressure.

3. Development of technical specifications and preliminary design of a multichannel acoustic emission system for monitoring cracking activity under both uniaxial and triaxial loading conditions. The system can be used to locate cracks (position, time, direction, and size) using quantitative acoustic emission theory.

4. Development of technical specifications and design of an experimental facility for testing materials at very low temperatures (down to -50^{o}C). The facility will also have capability to grown and prepare ice samples for mechanical testing.

Research Assistant/Thesis

Wu, Mao S., "Continum Modeling of Sea Ice."
SMCE 2/87

4. **Adhesively Bonded Joints in Construction Polymers**

Principal Investigator: **Dr. S. Shyam-Sunder**

Description of Project: This project is a comprehensive experimental and a theoretical investigation into the deformation and failure of adhesively bonded joints in construction polymers. Specifically, attention is focussed on elastomeric lap joints that are frequently encountered in waterproofing membranes on roofs. The project consists of:

(i) Experimental studies to characterize the mechanical response of elastomers,

(ii) Experimental studies to characterize the mechanical response of the adhesives,

(iii) Analytical and numerical studies to predict the response of the joint to externally applied loads, and

(iv) Lap joint tests and characterization of failure in the joints by a comparison of experimental studies with theoretical predictions.

A lap joint system consisting of Ethylene Propylene Diene Terpolymer (EPDM) substrates joined with Butyl adhesives has been chosen for detailed investigation in the present study.

Accomplishments/Products

- Development of a constitutive model for the mechanical response of EPDM membranes.

- Development of a constitutive model for the mechanical response of Butyl adhesives.

- Development of a one-dimensional model for the deformation of a lap joint under the action of shear and peel loads.

- Development of a numerical model to characterize the two-dimensional stress fields associated with deformation of the joint in shear and peel.

- Development the criteria of crack initiation in elastomeric lap joints.

- Development of a design methodology for efficient design of elastomeric lap joints.

Publications

Lakshmana Rao C., Connor J.J. and Shyam-Sunder S. (1991), "Failure initiation in EPDM Lap Joints in a Lap Shear Test," Third International Symposium on Roofing Technology, Montreal, Canada.

Lakshmana Rao C., Shyam-Sunder S. and Connor J.J. (1991), "Characterization of Bulk Properties of Butyl Adhesives", Journal of Adhesion, submitted for publication.

Lakshamana Rao C., Shyam-Sunder S. and Connor J.J., (1990), "Shear Deformations in Adhesively Bonded Elastomeric Lap Joints", Research Report No. R90-3, Department of Civil Engineering, Massachusetts Institute of Technology.

Research Assistant/Thesis

Rao, C. Lakshmana. Thesis Title: "Deformation and Failure of Adhesively Bonded Elastomeric Lap Joints" Degree: Doctor of Science, 2/92

5. Geosynthetic Reinforcement of Soil Masses

Principal Investigator: **Professor Andrew Whittle**

Project Description: The use of geosynthetic materials to reinforce soils in the construction of retaining walls, embankments, foundations and pavements, has been an era of rapid growth in the last ten years. This represents a combination of two highly successful innovations in foundation engineering practice: a) the use of new materials to facilitate construction processes and reduce costs; and b) strengthening of soil masses using tensile inclusions. One of the most fundamentally important but least understood aspects of soil reinforcement is the interaction between the soil and the reinforcing inclusion. The mechanisms of interaction are particularly complex for inclusions with non-linear and time dependent behavior.

The overall objective of this research is to develop a fundamental understanding of soil-reinforcement interaction and hence provide a rational basis for selection of geosynthetic reinforcing materials in design. With support form the ARO/PACT program (October 1988 to January 1991) we have initiated research efforts to develop more reliable methods for predicting reinforcement stresses through an integrated program of experimental measurements and analytical modelling:

Existing laboratory tests, including direct shear and pullout devices, are primarily intended to characterize soil-reinforcement interaction in terms of the interface friction which is then used in limit equilibrium analyses. The tests are not well suited for estimating the loads which are transferred to the reinforcement at working stress levels. Primary limitations of the existing tests are due to a) non-uniformity of stress and strain within the soil, and b) lack of direct measurements of reinforcement loads. In order to overcome these limitations, we have designed and constructed a new test device refereed to as the APSR cell (Automated Plane Strain Reinforcement cell). The APSR cell has the unique capability of measuring directly the load distribution within reinforcements of various lengths, geometrics and orientations as the surrounding soil matrix is

deformed in plane strain shearing. Extensive proof testing of the APSR cell has included a) shear tests on unreinforced sand at a range of formation densities, and b) measurements of stress distributions for steel sheet reinforcements of varying lengths. A similar program of tests are now in progress to evaluate load-transfer characteristics for a polymeric heat inclusion ('geomembrane').

In parallel with he experimental program, analytical models have been developed in order to predict the load distribution within the reinforcement based on known properties of the soil and reinforcing materials. Initially, the analytical work has assumed linear, isotropic, elastic properties for the reinforcement and soil matrix and has considered a planar inclusion oriented parallel to the minor principal stress. For this situation, closed form solutions for the reinforcement stresses have been developed using methods of shear lag analysis. The predicted tensile stresses are in excellent agreement with numerical solutions obtained using finite element analyses, and have subsequently been extended to consider slippage at the soil-reinforcement interface. The analytical solutions provide a framework for interpreting the experimental measurements of load-transfer in the APSR cell. Work is currently in progress to extend the shear lag analysis and include more realistic constitutive properties of the soil and reinforcing material.

Accomplishments/Products

This research assumes that a fundamental understanding of soil-reinforcement interaction is necessary in order to predict reinforcement stress at working load levels and hence provide a more rational basis for selection of geosynthetic materials in design. A detailed review of existing analyses an design methods in the literature has shown that the key contributions required to achieve these goals are: a) the accurate measurement of load transfer under well controlled laboratory conditions; and b) the development of an analytical framework capable or predicting reinforcement stresses based on known propertied of the soil matrix and reinforcing materials. Research work in this project has addressed both of these tasks and has accomplished the following:

1. A new laboratory test device, the APSR cell, has been designed and constructed in order to measure load-transfer for a variety of reinforcing materials. overall, the APSR cell represent a very significant advance over existing devices for evaluating soil-reinforcement interaction and includes the following design features: a) Tests can be performed on inclusions up to 450mm in length at applied stress of 500kPa, which are typical of field situations. b) The boundary tractions are applied through lubricated pressure bags which ensure a high degree of uniformity of the exterior soil stresses and enable the sample to be sheared at axial strains up to 10%, which are sufficient to cause failure of the soil. c) Plane strain conditions are controlled using an innovative active system with pressurized diaphragms which reduce the overall thickness of the side walls. d) The APSR cell is instrumented with an external load cell to measure the maximum tensile force in the reinforcement. Instrumentation can also be designed to measure local strains and/or stresses at locations along the inclusion. e) Additional measurements of deformations and strains in both the soil and reinforcement are obtained using radiographic measurements. f) The APSR cell is full automated and includes seven independent feedback control systems which are controlled by a single microcomputer and three custom-built feedback control circuits. g) The sand sample is prepared by ranging particles through an assembly of sieves and is designed such that soil can be sheared wither normal to the direction of deposition (cross-anisotrpic properties).

2. An extensive program of proof testing has been conducted in order to evaluate the capabilities of the APSR cell. This work has included: a) debugging the control, data acquisition and measurement reaction software which have been custom written for the cell; b) perform tests on unreinforced sand to evaluate design parameters of the cell including uniformity of stress and strain, minimization of wall friction, plane strain feedback control, and test repeatability; and c) compare measured data with

behavior reported previously in other shear devices in order to establish the reliability of material properties measured by the APSR cell. A parallel program of in-isolation tests have also been perform don the reinforcing materials in order a) to characterize reference material properties, and b) to develop instrumentation for measuring local strains within the reinforcing inclusions.

3. Measurements of load transfer in the APSR cell have been obtained from a test program on steel sheet inclusions. The test data include stress distributions for reinforcement s of varying lengths and for sand sheared at a range of formation densities. These tested represent the first reliable, direct laboratory measurements of load transfer in reinforce soil. The data are used to evaluate analytical models of soil-reinforcement interaction and hence provide a basis for estimating reinforcements stresses in field situations.

4. Analytical solutions have been developed to predict the load distribution a long a planar inclusion in a biaxial compressive stress field based on specified (elastic) properties of the soil matrix and reinforcing materials. This work represents the first application of shear lag analysis in the field of reinforced soils. Predictions of load transfer from the proposed analysis are in excellent agreement with numerical calculations using finite element methods and have been used to interpret the APSR measurements. The shear lag analyses have been extended a) to include frictional slippage at eh soil-reinforcement interface, and b) to analyses the stress transfer in conventional pullout tests.

Publications

Whittle, A.J., Germaine, J.T., Larson, D.G. and Abramento, M. "Measurement and Interpretation of Reinforcement Stresses in the APSR Cell," Earth Reinforcement Practice, Ochiai, Hayashi & Otani (eds) 1992 Balkema, Rotterdam ISBN 9054100931

Abramento, M. and Whittle, A.J. "Shear Lag Analysis of a Planar Soil Reinforcement in Plane Strain Compression", ASCE Journal of Engineering Mechanics, Nol. 119, No. 2 February 1993.

Whittle, A.J., Larson, D.G. and Germaine, J.T. "A New Laboratory Device for Evaluating Soil Reinforcement,' abstract submitted ASTM symposium on Geosynthetic Soil Reinforcement Testing Procedures, San Antonio, Texas, January 1993.

Research Assistants/Theses

Larson, Douglas (supported by ARO/PACT: October 1988-Jan.1992)
Thesis Title: "A Laboratory Investigation of Lord Transfer in Reinforced Soil" Ph.D. 9/92

Abramento, Mauricio has also contributed to this research in the area of analytical modelling. Mauricio was supported by the Brazilian Government through a CNP Fellowship.
Thesis Title: "Analysis and Measurement of Stresses in Planar Soil Reinforcements," Ph.D. 5/93

6. **Advanced Fiber-Reinforced Polymer Composite Materials in the Rehabilitation of Structures**

Principal Investigator: **Thanasis C. Triantafillou**

Description of Project: The aim of this research project is to study the short-term (static) and long-term (creep) mechanical behavior of reinforced concrete and wood members strengthened with composite materials. The concept involves the use of unidirectional fiber-reinforced plastic (FRP) sheets bonded externally on the tension zones of structural elements using epoxy adhesives, offering several advantages over traditional methods of strengthening, such as the use of materials which are corrosion immune, lightweight, electromagnetically neutral, and at the same time maintain a high strength and stiffness to weight ratio. The study involves a combination of analytical, numerical and experimental developments. Various types of composites are considered in the analytical and numerical part of the study (glass, aramid or carbon fibers bonded together with a matrix such as epoxy, polyester, vinylester, etc.), while the results are verified experimentally using concrete beams and wood beams and beam-columns strengthened with carbon FRP.

Accomplishments/Products

Use of FRP as external reinforcement of reinforced concrete and wood structures through the application of thin FRP sheets on the tension faces of members using epoxy adhesives appears to be a very promising solution for both rehabilitation and applications as well as new

constructions. Analytical models are available for the analysis and design of reinforced concrete and wood members strengthened with FRP sheets, for both short-term and long-term loads. The models account for various failure mechanisms of all the constituent materials and were verified experimentally in the laboratory. In addition, the work established a procedure for the selection of the appropriate FRP material (type and geometry) to be used in a specific rehabilitation/strengthening or new project. The products of the work include software packages for the analysis and design of FRP-strengthened structural members as well as a new laboratory facility for creep testing of beams reinforced with composite sheets.

Publications

Journal Publications:

Triantafillou, T.C. and Plevris, N. (1992) "Strengthening of R/C Beams with Epoxy-Bonded Fiber-Composite Materials," to appear in Materials and Structures, RILEM.

Plevris, N. and Triantafillou, T.C. (1992) "FRP-Reinforced Wood as Structural Material," to appear in the Journal of Materials in Civil Engineering, ASCE.

Triantafillou, T.C. and Plevris, N. (1992) "Creep Behavior of Reinforced Concrete Beams strengthened with Composite Matls" in preparation.

Plevris, N. and Triantafillou, T.C. (1992) "Creep Behavior of Wood Members Reinforced With Epoxy-Bonded Composites" in preparation.

Technical Reports:

Plevris, N. and Triantafillou, T.C. (1991) "Strengthening and/or Reinforcing Concrete and Wood Structures with Advanced Composites," Research Report R91-04, Department of Civil Engineering, M.I.T., Cambridge, MA, January 1991.

Triantafillou, T.C. and Plevris, N. (1992) "Advanced Fiber-Reinforced Polymer Composites as External Reinforcement of Structures: Long-Term Behavior" Research Report, Department of Civil Engineering, M.I.T., Cambridge, MA, in preparation (available: January, 1992).

Conference Papers:

Triantafillou, T.C. and Plevris, N. (1991) "Post-strengthening of R/C Beams with Epoxy-Bonded Fiber-Composite Materials," presented at the ASCE Specialty Conference on Advanced Composites for Civil Engineering Structures, Las Vegas, NV, Jan. 31-Feb. 1 1991.

Research Assistant

Plevris, Nicholas
Title of Master Thesis: "Strengthening and/or Reinforcing Structures With Fiber-Reinforced Plastic Composite Sheets"SMCE 2/91
Title of Ph.D. Thesis: Time-Dependent Behavior and Desing of Rinforced Concrete and Wood Structure Strenthened with FRP Laminates" Ph.D. 5/93

7. **Precision of Scissor-Link Deployable Structures**

Principal Investigator: Professor Jerome J. Connor

Description of Project: Deployable space frames consisting of straight bars that are stable and stress-free in both the deployed and the folded configuration, but develop nonlinear stresses due to geometric incompatibilities during deployment, are investigated. The objective is the formulation of a systematic methodology for their geometric and structural design. The approach for geometric design involves formulation of analytical constraint equations that are solved with numerical iterations. The approach for structural analysis includes finite element modeling, nonlinear analysis during deployment, linear analysis in the deployed configuration, and for structural design, the use of approximate, simple models for preliminary design, and exact finite element models for final design.

Accomplishments

Key accomplishment have included: formulation of a generic geometric design methodology for any shape in the deployed configuration; completion of parametric studies; and improvement of equivalent continuum model in the deployed configuration.

Publications

Gantes, C., Connor, J., and Logcher, R., "Combining Numerical Analysis and Engineering Judgment to Design Deployable Structures, Computers and Structures." (accepted for publication).

Gantes, C., Connor, J. and Logcher, R., "Simulation of the Deployment Process of Multiunit Deployable Structures, and Cray Channels." (accepted for publication).

Gantes, C., Connor J. and Logcher, R., "Geometric and Structural Design Considerations for Deployable Space Frames, "MARAS '91, International Conf. on Mobile and Rapidly Assembled Structures, U.K. April '91.

Gantes, C., Connor, J. and Logcher, R., "Finite Element Analysis of Movable, Deployable Roofs and Bridges," Third Biennial Symposium on Heavy Movable Bridges, St. Petersburg, FL, Nov. '90.

Research Assistant/Thesis

Gantes, Charalambos, Thesis title: "A Design Methodology for Deployable Structures."
Ph.D. May 1991

C. COMPUTERS AND INFORMATION TECHNOLOGY

1. Distributed and Integrated Environment for Computer-Aided Engineering (DICE)

Principal Investigator: **Professor Duvvuru Sriram**

Description of Project: Problem: Engineering projects, in general, involve a large number of components and the interaction of multiple technologies. On a single project, interacting design technologies often come from separate firms or functional groups within a firm, and there is little coordination between various participants. Typically, engineers find coordination among themselves difficult and they leave this task to the manufacturing personnel. Potential conflicts among participants are often unrecognized until manufacturing begins. Several undesirable effects are caused by this lack of coordination. For example, in the construction industry the lack of communication and coordination leads to the following problems: 1) the construction process is slowed, because work stops when a conflict is found; 2) prefabrication opportunities are limited, because details must remain flexible; 3) opportunities for automation are limited, because capital intensive high speed equipment is incompatible with work interruptions from field recognized conflicts; 4) rework is rampant, because field recognized conflicts often require changes; and 5) conservatism pervades design, because designers provide excessive slack in component interfaces to avoid conflict.

Goal: The current cost trends in computer hardware will make it possible for every engineer to have access to a high performance workstation. Hence, it is my goal to provide a computer-based framework which will: 1)

facilitate effective coordination and communication between various disciplines involved in engineering; 2) capture the decision making process of individual designers, i.e., what information was used, how it was used and what did it create; 3) forecast the impact of design decisions on manufacturing or construction; 4) provide designers interactively with detailed manufacturing process or construction planning; and 5) develop a few domain dependent knowledge-based systems (design agents) for illustrating my approach.

Approach: To achieve the goals outlined above, a system architecture - DICE (Distributed and Integrated environment for Computer-aided Engineering) - based on current trends in programming methodologies, object-oriented databases, and knowledge-based systems was developed. DICE can be envisioned as a network of computer and users, where the communication and coordination is achieved through a global database and a control mechanism. The global database in DICE is an object-oriented Blackboard, which also includes control activities, and the design agents are termed as Knowledge-Modules. The Blackboard is partitioned into Coordination, Solution, and Negotiation Blackboards, while the Knowledge Modules are categorized into: Strategic, Critic, Specialist and Quantitative KMs.

Publications

Sriram, D., Logcher, R., Groleau, and Cherneff, J., "DICE: An Object Oriented Programming Environment for Communication, Coordination and Control in Computer Aided Engineering", To appear in Artificial Intelligence Approaches to Engineering Design, Edited by Tong, C. and Sriram, D., 1991.

Sriram, D. and Groleau, N., "Object Oriented Databases for Cooperative Design, Sixth ASCE Conference on Computing in Civil Engineering, Atlanta, Georgia, September, 1989.

Sriram, D. Logcher, R., and Groleau, N., "A Framework for a Computer Integrated Design and Construction System:, International Conference on Computational Engineering Science, Atlanta, Georgia, April 1988 (Invited).

Research Assistants

Groleau, N., "A Blackboard Architecture for Communication, Coordination, and Control in Design", January 1989. Due to a shift in emphasis ARO decided not to continue with the DICE project in Summer 1988 and N. Groleau was shifted to Dept. of Aero. and Astro.

2. Computer-Aided Virtual Construction

Principal Investigators: **Professor John D. Williams**
Professor Alex Pentland

Description of Project: The concept of Virtual Construction is to allow designers and engineers to interactively simulate complex, 3-D situations using computer workstations. The idea is that by providing immediate feedback about the viability of a design -- even if that feedback is only approximate -- the design loop can be shortened and the average design quality improved. The main technical focus is to develop methods for approximate physical simulation that have much better simulation complexity than standard exact simulation methods.

Accomplishments/Products:

The Thingworld Modeling and Simulation system has been produced. This system, which runs on Sun work stations in Lisp and C, is in use by more than 30 universities and 5 companies.

Publications

Sclaroff, S., and Pentland, A., "Generalized Implicit Functions for Computer Graphics," ACM Computer Graphics, Vol. 25, No. 2, pp. 247-250, 1991.

Friedmann, M., Starner, T., and Pentland, A., "Synchronization in Virtual Realities," TelePresence, Vol. 1, (to appear).

Pentland, A., "Computational Complexity Versus Simulated Environments"ACM Computer Graphics, Vol. 24, No.2, pp. 185-192, 1990.

Pentland, A., (1990) "Computational Complexity Versus Simulated Environments," ACM Computer Graphics, Vol. 24, No. 2, pp. 185-192. June 1990.

Pentland, A., Essa, I., Friedmann, M., Horowitz, B., Sclaroff, S., "The Thingworld Modeling System: Virtual Sculpting by Modal Forces," ACM Computer Graphics, Vol. 24, No. 2,pp. 143-144, June, 1990.

Pentland, A., and Williams, J. "Good Vibrations: Modal Dynamics for Graphics and Animation,"ACM Computer Graphics Vol. 23, No. 4, pp. 215-222, August, 1989.

Pentland, A., and Williams, J. "Virtual Construction," Construction, Vol. 3, pp. 12-22., Fall 1988.

Pentland, A. and Williams, J. "Perception of Non-Rigid Motion: Inference of Shape, Material, and Force," Eleventh International Joint Conference on Artificial Intelligence, Proceedings, Volume 2, August 1989.

Pentland, A. and Williams, J., "Fast Simulation on Small Computers: Model Dynamics Applies to Volumetric Models." Modeling and Simulation, Volume 20, Part 5, May 1989.

Pentland, A. and Williams, J., "Virtual Manufacturing," NSF Engineering Desing Research Conference, June 1989.

Williams, J.R. and Pentland, A.P., "Object Representation for Desing-Unifying Cubes and Spheres." COMPLAS'89, 2nd International Conference on Computational Plasticity, September 1989.

Williams, J.R. and Pentland, A. P., "Superquadric Object Representation of Dynamics of Multi-Body Structures," ASCE Strucuturs '89 Annual Conference, May 1989.

Williams, J.R. and Pentland, A.P., "Animation and Physical Modeling Strategies for Design," NUMETA '90, January 1990.

Research Assistants/Thesis

Essa, Irfan, September, 1990-Present, Masters Thesis Title: "Contact Detection, Collision Forces and Friction for Physically Based Virtual World Modeling"SMCE 6/90
Current Status:Ph.D. Student, MIT Media Lab

Sclaroff, Stanley (MS Candidate)

3. Quality in Design of Construction Facilities

Principal Investigator: **Professor Jerome Connor**

Description of Project: Many problems during the construction process can be avoided by "designing" to known construction processing capabilities. One of the reasons why this aspect is not considered is the separation between design and construction that has historically existed in the industry. Another reason is the inability of a single individual to assimilate all the knowledge that is needed to build what is designed, and to communicate the intent of the design to the contractor. The goal of this projects is to develop and implement a methodology for evaluating the constructability of basic structural components with respect to both their individual fabrication and assembly processes as well as their assembly into an overall structural system, using a multi-level knowledge-based system approach.

Accomplishments/Products

An object-oriented prototype version of a constructability reviewer for the design of cast-in-place, reinforced concrete buildings has been developed. The influence of construction processes on design decisions is obtained through expansion of the design objectives to include some measures of construction cost and expansion of the design process to encompass the domain of construction planning. Constraints imposed by the architect, behavioral considerations, and construction processes prune the design options. Information theory, after Shannon, provides a quantitative decision-making criteria for selecting the best option; i.e., the option with the highest probability of satisfying design requirements. Use of information content allows for a homogeneous treatment of both design and construction planning decisions throughout the design process.

Publications

Connor, J. and Albano, L., "A Strategy for Construction-Oriented Design", Proceedings of the MIT-JSME Workshop on Cooperative Product Development, MIT, Cambridge, MA , November 1989.

Connor, J. and Albano, L., "A Computer-Based Methodology for Integration of Design and Construction," Journal of Computing in Civil Engineering, ASCE, submitted for publication, October 1989.

Albano, Leonard., J.J. Connor, and N.P. Suh, "A Framework for Performance-Based Design" Research in Engineering Design (1993) 5: 105-119.

PACT Fellow/Thesis

Albano, Leonard D., Thesis title: "An Aximotic Approach to Performance-Based Design."Ph.D. 6/92

D. REMOTE SENSING & DIAGNOSTICS

1. Assessment of In-Situ Conditions Using Wave Propagation Techniques

Principal Investigator: **Dr. Kenneth R. Maser**

Description of Project: The overall objective of this research was to stimulate the development of wave propagation sensor techniques for the evaluation of in-situ conditions. Assessment of conditions in the built environment is critical to the management of

infrastructure, and there are significant opportunities for developing such sensor technology which have yet to be fully exploited. This research was directed towards providing a developmental framework, and an associated set of developmental tools, applicable to wave propagation techniques. Such techniques include seismics, sonics and ultrasonics, and impulse radar. The research focused on the development of tools in two areas: (1) predictive analytic models and waveform synthesis techniques, and (2) laboratory evaluation techniques. The development of these tools was specifically oriented towards applications involving identification, location, and characterization of regular and irregular subsurface anomalies. Originally this research was conceived in an effort to exploit commonalities between electromagnetic and mechanical wave propagation techniques. This perspective was found to be too broad at this stage of the research. Such a perspective would become more meaningful when a better understanding of specific properties of the media is achieved. The first year of this research focused on the following two areas:

(i) Electromagnetic wave propagation in construction materials, and

(II) Seismic wave propagation for subsurface condition assessment.

Accomplishments/Products

Significant progress was made in the development of analytic tools for waveform synthesis. A radar waveform synthesis computer program, previously developed under an earlier project, was modified to incorporate the effect of reflection from reinforcing steel (rebars) in a bridge deck. In the program, rebar reflection was modeled using a Scattering Attenuation Function (SAF) based on geometric optics principles. To verify the applicability the SAF for the case of rebars, laboratory experiments were conducted using two types of antenna, namely the air-coupled horn-type (ACH) antenna and the ground coupled dipole (GCD) antenna. For the ACH antenna, the results predicted by SAF were within 10 to 15% of the experimental value for cylinders with radii ranging from 1 to 3 cm which corresponds to rebar sizes ranging from #6 to #11. For the GCD antenna, similar results were achieved, but with a deviation of 20 to 25% in the 1 to 3 cm radius range.

These findings were incorporated into a synthesis program which was then used to conduct a parametric study representing bridge deck deterioration conditions. This parametric study assumed a bridge deck with a total concrete thickness of 8 inches overlain by asphalt. The thickness of asphalt was varied from between 1.5 and 3.5 inches, and the cover concrete thickness (portion of concrete above the top rebar grid) was varied between 1.0 and 3.0 inches, representing typical conditions encountered in the field. Comparisons of synthesized waveforms generated in the parameter study with field waveforms obtained in a survey of concrete bridge decks in New England indicated a need for a stronger emphasis in future research on characterization and modeling of electromagnetic properties of concrete.

The second area of research involved the study of transmission characteristics of seismic boundary waves at the interface between two dissimilar media. An attempt was made to understand the generation and propagation of Stoneley waves more extensively for the purpose of synthesizing waveforms. Such synthetic waveforms could then be used to theoretically study the effect of small amount of leakage from a tank bottom. A review of literature revealed that waveform synthesis for Stoneley waves would be mathematically complex, and involve considerable time and effort. Thus it was decided to discontinue this work in favor of further work dealing with electromagnetic waves.

Publications

Maser, Kenneth R., and Halabe, U., "Assessment of In-Situ Conditions Using Wave Propagation Techniques", December 1987, CCRE/PACT Report # 87-32.

Research Assistants/Thesis

Halabe, Udaya B., "Detection of Leakage From Large Storage Tanks Using Seismic Boundary Waves," AMXW 2/88; and "Condition Assessment of Reinforced Concrete Structures Using Electromagnetic Waves," Ph.D. 2/90.

2. The Role of Uncertainty in the Management of Infrastructure Facilities

Principal Investigator: **Professor Sue McNeil**

Description of Project: The purpose of the research was to develop, a comprehensive modeling framework that includes uncertainty in all phases of the infrastructure management process for transportation facilities. The representation of the process developed in the research applies to many different types of infrastructure including roads, pipelines, waterways and rail. Thus the project developed a general approach to infrastructure management although the concepts were derived and illustrated using elements of transportation infrastructure such as highways, bridges and rail.

Accomplishments/Products

An Infrastructure Management Process comprised of five components was defined. These components include: data collection and monitoring; impacts modeling; application of impact models; strategy selection; and strategy implementation. In the steady state when the facility is mature and sufficient data is available to allow model estimation, the process can be viewed as a dynamic system with feedback to facilitate the updating of models as experience is gained with strategies that have been implemented.

The research was successful in defining a comprehensive approach to modeling uncertainty in infrastructure management which includes:

- identification of the elements of the process that are influenced by uncertainty;
- recognition of the sources of error and randomness in the process;
- review of predictive and explanatory models that account for uncertainty in the process; and
- development of a comprehensive framework that explicitly includes uncertainty in stochastic exogenous variables and endogenous variables by modeling the variables as random variables with a deterministic and stochastic error component.

The results of the research can be used in decision making using optimization approaches found in the literature that are based on expected values. However, before the research can be implemented, additional research is required to: hypothesize and test distributional assumptions for exogenous variables such as weather and inherent variability; and develop and estimate functional forms for the models developed in this phase of the research.

In the development of the comprehensive framework, the research has also identified the need for an estimable, rational indicator of condition and the importance of uncertainty in the selection of technologies for data collection.

Publications

McNeil, Sue, Humplick, F., Ramaswamy, R.; "The Role of Uncertainty in the Management of Infrastructure Facilities," December 1987, CCRE/PACT Report # 87-31.

Humplick, F., Brisson, F., and McNeil, S., "Pavement Maintenance and Rehabilitation Decisions Using an Expert System that Learns," Working Paper, M.I.T., Department of Civil Engineering, 1987.

Ramaswamy, R., "A Stochastic Model for Infrastructure Deterioration in Continuous State and Continuous Time," Working Paper, Center for Transportation Studies, M.I.T., 1987.

Ramaswamy, R., "Modeling Deterioration of Concrete Bridge Decks," Working Paper, Center for Transportation Studies, M.I.T., 1987.

McNeil, S., Humplick, F., "Evaluation of Automated Inspection Systems for Pavement Surface Distress," Paper presented at the 14th ARRB Conference, Canberra, September 1988.

Research Assistants/Theses

Humplick, Frannie F., "Theory and Methods of Analyzing Infrastructure Inspection Output: Application to Highway Pavement Surface Condition Evaluation," Ph.D. 9/89.
Current Status: Infrastructure Systems Analyst, World Bank

Ramaswamy, Robert, "Estimation of Latent Performance From Damage Measurements," Ph.D. 6/89.

3. Wave Propagation Techniques for Infrastructure Technology

Principal Investigator: **Professor Eduardo Kausel**

Description of Project: The goal of the PACT project last year was to develop analytical and numerical techniques for the detection of delamination cracks in concrete and, more in general, to locate and size cavities and inclusions in man-made and natural materials. The methods are based on the use of acoustic and electromagnetic signals, in the form of pulses or sine waves. Forward problems were addressed first, in which the measured signals are predicted under known conditions using wave propagation theory. Based on such solutions, inversion techniques have been developed for the estimation of unknown geometric and mechanical parameters.

Accomplishments/Products

A significant achievement has been the development of a constitutive model for the propagation of electromagnetic waves in concrete, including the effect of various constituents in the mixture and of intruded chloride solution. This model has been verified by means of experiments with wet sand. Inversion procedures based on the model are under study.

Another area of current work is the imaging of defects, cavities and embedded structures. Interesting results using sonic waves have been obtained concerning the detectability of the boundary, the size and the material properties of inclusions and cavities.

Publications

Halabe, U.B., Maser, K., Kausel, E., "Propagation Characteristics of Electromagnetic Waves in Concrete," January 1989.

Research Assistants/Theses

Ghibril, Riad N., "Scattering of Elastic Waves by Steel Reinforcement in Concrete", MS, February 1990

Halabe, Udaya B., "Condition Assessment of Reinforced Concrete Structures Using Electromagnetic Waves," Ph.D., February 1990.

4. **Assessment of Radar Technology for Concrete Deck Damage**

Principal Investigator: **Prof. Daniele Veneziano**

Description of Project: Much effort has been expended to collect and use radar data for the detection of deterioration in asphalt covered concrete decks. Conclusions by different authors are not unanimous. A large dataset was compiled at MIT for decks throughout the New England area. The uniqueness of the dataset is that it includes not only radar waveforms, but also maps of actually damaged or repaired deck areas. The scope of the project was to use these data to statistically determine whether radar can reliably detect deteriorated conditions. Considerable effort was devoted to cleaning up and appropriately digesting the original data. In this process, several of the surveyed decks had to be excluded because of unreliable radar data on deterioration information. Several statistical techniques were used to compare radar signals from deteriorated and non-deteriorated areas. In order to avoid possible biases due to peculiarities of the decks, the analyses for individual decks was repeated.

Accomplishments/Products

The firm conclusion was reached that radar is not a reliable device for the stated objective and therefore recommend that, unless it is modified, radar inspection not be used in the future to detect concrete delamination. In spite of the negative conclusions, radar can be used to reliably detect boundaries between layers with different dielectric properties. For example, one can detect quite well the location of the asphalt-concrete interface and, less well, the plane of the rebars and the existence of multiple asphalt layers. Possible extensions of the project are: (1) Use of radar to estimate geomeric parameters of the decks, including the density of the rebars; (2) Use or radar in problems where layer identification is the main objective (e.g., pavements); and (3) Use of radar in conjunction with other techniques (e.g., sonic).

Research Assistants

Elvin, Alex Allan, "Assessment of Radar Technology for Concrete Damage."
MS, February 1990.

5. **Automated Non-Destructive Testing of Concrete Using Sonic Methods**

Principal Investigators: **Professors Eduardo Kausel and Daniele Veneziano**

Description of Project: This project is the outgrowth, but not a direct continuation of work done previously by Professors Kausel and Veneziano under the PACT program. The work in this project focuses exclusively on the use of sonic methods for assessing the conditions of concrete decks and is aimed at developing an automatic system. Several tasks are underway including: the development of predictive models based on physical principles; the development of signal processing techniques to extract diagnostic characteristics from actual records; and development of methods for using signal features to assess and classify the condition of the concrete (e.g., presence/absence of delaminations, presence;absence of fractured concrete, nature of bonding materials, etc.)

Research Assistant

Geng, Yiping, " Finite Element Assessemnt of Cracks and Delaminations in Concrete Bridge Decks by the Impact-Echo Method," SMCE 3/92

Tadeu, Antonio,"Modelling ans Seismic Imaging of Buried Structures", Ph.D. 2/92

6. **Automated Analysis of Pavement Distress Data**

Principal Investigator: **Prof. Haris N. Koutsopoulos**

Description of Project: Transportation infrastructure maintenance has drawn increased attention in the last few years in response to the rapid deterioration of the country's huge road network. Research efforts in this area focus on the development of pavement management systems. The essential components of any pavement management system are: data collection technologies, data processing capabilities,

and models for pavement performance prediction and resource allocation.

An important category of data collected for pavement management is distress data. currently pavements are usually manually inspected for collection of surface distress data. this form of inspection is slow, labor intensive and expensive with low sampling rate. It is also subjective with low consistency between surveys and poor repeatability. These drawbacks result in inaccurate pavement condition assessment and subsequently wrong maintenance decisions.

To eliminate the drawbacks of manual inspection, automation of the process has been suggested and it is currently receiving increased attention due to its potential to provide highway agencies accurate and detailed data on pavement condition at reasonable cost. Various systems exist or are under development to record the surface of the pavement on video tape or photographic film and subsequently analyze it either manually in a laboratory or automatically using image processing and pattern recognition methods. systems differ with respect to their degree of automation, accuracy, technology used, resolution and types of data collected. Examples of such systems are PASCO and PAVETECH.

The objective of this research is to develop methods for automated analysis of pavement data collected by visual devices. Automated analysis of pavement images requires processing at two levels: the microscopic level, which is concerned with the processing of individual images and their classification to corresponding distress types. Automation of this process however provides, in most cases, a large amount of data (usually 100% coverage of highway segments). Since the main use of the collected data is as input to other components of the infrastructure management process (pavement evaluation, deterioration modeling, future condition prediction, and appropriate maintenance and rehabilitation strategy selection) there is also need for methods to aggregate the information so that it can be used more effectively by the agencies. consequently, in addition to the need for processing

automatically the individual images collected by the various technologies, another important and very practical need is for methods to analyze interpreted data in a systematic way so that it can be further used by the highway agencies. Hence the macroscopic level, based on the results obtained from the macroscopic level, summarizes the information in a useful way.

The necessary components of an automated inspection system at the microscopic level, include: image enhancement (improvement of digital images and preparation); segmentation (extraction of objects of interest from the background); and classification to a distress class and quantification (measurement of the extent and severity of the distresses). At the macroscopic level, the system includes models for the identification and development of spatial relationships among distresses. Such relationships are important for aggregating and reducing data without loss of useful information.

Publications

Koutsopoulos, H.N. and I. El Sanhouri, "Methods and Algorithms for Automated Analysis of Pavement Images," forthcoming in Transportation Research Record.

Koutsopoulos, H.N., I. El Sanhouri and A.B. Downey, "Analysis of Segmentation Algorithms for Pavement Distress Images," forthcoming in Journal of Transportation Engineering.

Koutsopoulos, H.N. and A.B. Downey, " A Primitive Based Approach to the Classification of Pavement Distress Images," forthcoming in Journal of Transportation Engineering, May 1991.

Koutsopoulos, H.N. and R. Mishalani, "A Methodology for Automated Analysis and Spatial Representation of Pavement Distress Data," submitted for publication Transportation Research Record, August 1991.

Koutsopoulos, H.N., I. El Sanhouri, A. Downey, "Segmentation Algorithms for Pavement Images," in Proceedings of the International Conference on Highway Informatics, Paris, France, March 1990, Presses de l'ecole nationale des ponts et chaussees.

Koutsopoulos, H.N., R.G. Mishalani and A.B. Downey, "Automated Analysis of Pavement Distress Data," Proceedings of the Second International Conference on Applications of Advanced Technologies in Transportation Engineering, Minneapolis MN, August 1991.

Koutsopoulos, H.N., V.I. Kapotis, A.B. Downey, " Improved Methods for Classification of Pavement Distress Images" In Transportation Research C. Vol. 2, No. 1 pp 19-33, 1994.

Research Assistants/Theses

El Sanhouri, Ibrahim, "Computer-Based Segmentation and Interpretation of Pavement Surface Distress Images," SMCE, April 1990.

Downey, Allan B. "Application of Statistical Pattern Recognition to Pavement Distress Identification," SMCE, August 1990.

Kapotis, Vassilios. "Classification Methods for Pavement Distress Images," MST 6/92.

Mishalani, Rabi. "Spatial Distribution of Pavement Distresses," Ph.D. 9/93.

7. Theory and Methods for Analyses of Infrastructure Performance and Maintenance Strategies

Principal Investigator: **Professor Moshe Ben-Akiva**

Description of Project: The primary motivation for our research is the emergence of a large number of automated technologies to collect information on infrastructure facility conditions (such as Video, Laser, Radar and Infrared technologies). This has made available a large quantity of data for the analysis of infrastructure performance. These technologies require new computer methods to process and reduce their output to a manageable size which is meaningful to decision-making. On the other hand, existing approaches to performance analysis are based on subjective indices using predetermined set of indicators, which were selected at a time when less developed data collection technologies were used. There is a need for an improved performance analysis methodology to exploit these enhanced data collection capabilities.

Before adapting new data collection technologies,their accuracy and precision must be analyzed. The results of such an analysis serve several purposes. First, they will be an input into a cost-effectiveness evaluation of new infrastructure inspection technologies, with the aim of selecting among them. Secondly, a knowledge of the accuracy and precision of the measurements made by these technologies must be included in t he maintenance and rehabilitation (M&R) strategy selection process, to incorporate the risk element in decisions which use these measurements as input. Finally, any methods to determine the frequencies for the

inspection of infrastructure facilities with these technologies must be based on the knowledge of their precisions. In this project we have developed a methodology which addresses these needs. This methodology will be used to evaluate progress and innovation in infrastructure inspection and maintenance technologies. It is also intended to be used by the agencies for the management of infrastructure facilities.

The infrastructure management process can be divided into three areas: data collection and inspection; performance analysis and forecasting; and M&R and inspection strategy selection. The objective of our research is to develop an analysis system to support this infrastructure management process and to assess alternative infrastructure inspection and M&R technologies. We have developed a new approach to infrastructure analysis with the following main facets:

- the key variable in the process, facility performance, is treated as latent variable, which manifests itself through measured performance or condition indicators;
- the errors and uncertainties in infrastructure condition measurement and performance analysis are explicitly analyzed, and taken into account in the decision-making process;
- to account for the interaction between the two decisions, inspection and maintenance strategies are jointly selected within an optimization algorithm.

Accomplishments/Products

This project had made seminal contributions in the following three areas of research:

- Data Collection and analysis
  - Formulated a methodology to estimate both the systematic and random measurement errors and demonstrated the significance of these errors.
  - Bias correction of inspection output and calculation of confidence interval around the corrected values.
  - Selection of cost-effective technologies.
  - Application of this methodology to pavement condition assessment technologies.

- Performance modeling
  - Formulated a latent performance modeling framework and statistical estimation procedure.
  - Captured the simultaneity of maintenance and deterioration mechanisms in the model system to get reasonable parameter estimate.
  - Flexibility in the selection of facility condition indicators.
  - A framework to discretize the latent state space using latent profile models was investigated.
  - Application to pavement performance analysis.
- Decision making.
  - Formulated a decision model for the joint selection of M&R and inspection activities.
  - Uncertainty in both the inspection output and facility performance model accounted for in decision-making.
  - The effect of forecasting and measurement uncertainty on life cycle costs has been quantified.
  - Computer implementation of the joint inspection and maintenance decision model. The computer model was tested on a number of case studies, where superior results were obtained compared to existing approaches, as it accounts for uncertainty in inspection output. A parametric study with different precisions measurement models and measurement technologies, revealed the existence of substantial financial benefits of having better information for decision making, resulting from the enhanced precision or performance models and measurement technologies.

These contributions have been documented in a number or professional papers which either have been published or in the process of publication, and have been presented to the research community through seminars at other universities and presentations at conferences. A summary of our research efforts is presented in Appendix I (paper submitted to ASCE Journal of Transportation Engineering). Our research in this project has been the basis of three Ph.D dissertations, by Rohit Ramaswamy, Frannie Humplick and Samer Madanat. A fourth student, Dinesh Gopinath, is expected to complete a M.S. thesis in this area in January 1992.

Publications

Ben-Akiva, M. and R. Ramaswamy (19910): "Estimation of Latent Pavement Performance from Damage Measurement", in Proceedings of the Third International Conference on Bearing Capacity of Roads and Airfields, Trondheim, Norway, 1990. An earlier and extended version of this paper appears in Selected Proceedings of fifth World Conference on Transport Research, Volume I, Yokohama, 1989.

Ben-Akiva, M. and R. Ramaswamy "An Approach for Predicting Latent Infrastructure Facility Deterioration" Transportation Science Vol. 27, No. 2, May 1993.

Ben-Akiva, M., F. Humplick, S. Madanat and R. Ramaswamy (1990):"Infrastructure Management Under Uncertainty: The Latent Performance Approach", Journal of Transportation Engineering, Vol. 119, No. 1, January/February 1993.

Ben-Akiva, M., S. Madanat, F. Humplick and R. Ramaswamy (1991)): "The Latent Performance Approach to Infrastructure Management", present at the 70th Annual Meeting of the Transportation Research Board, January 1991.

Ben-Akiva, M., F. Humplick: " A Methodology for Estimating the Accuracy of Inspection Systems", submitted to Transportation Science, April 1991.

Humplick, F., M. Ben-Akiva: "Measurement Error Modeling for Infrastructure Inspection Systems", submitted to the Sixth World Conference on Transport Research, Lyon, France, June 29 - July 3 1992.

Humplick, F.:" Identifying Error Generating Factors in Inspection Condition Evaluation", to be present at the 71st Annual meeting of the Transportation Research Board, January 1992.

Humplick, S., "Highway Pavement Condition Evaluation: Modeling Measurement Error", accepted for publication in Transportation Research, Part B., 1991.

Research Assistants

Ramaswamy, Rohit. "Estimation of Latent Pavement Performance from Damage Measurements," Ph.D., June 1989
Current Status: AT&T Bell Laboratories, Murray Hill, New Jersey

Humplick, Frannie. " Theory and Methods of Analyzing Infrastructure Inspection Output: Application to Highway Pavement Surface Condition Evaluation, " Ph.D., September 1989
Current Status: World Bank, Washington D.C.

Madanat, Samer. "Optimizing Sequential Decisions Under Measurement and Forecasting Uncertainty:Application to Infrastructure Inspection, Maintenance & Rehabilitation, " Ph.D., January 1991
Current Status: Will join the faculty of the Department of Civil Engineering, Purdue University, from January 1992.

Gopinath, Dinesh (S.M. expected 1992).Thesis Title: Modeling Infrastructure Performance and User Costs," (expected January 1992) Current Status: Graduate Student, Department of Civil Engineering

8. Assessment of Radar Technology for Determining Pavement Layer Thickness

Principal Investigator: Professor Moshe Livneh

Description of Project: The type of information needed for a network pavement management level system includes: (a) ride quality, (b) physical distress, (c) safety and (d) traffic volume and weight. As for the project level management system, additional information is required, which is the carrying capacity of the pavement structures. In order to obtain this information, it is necessary to accompany the non-destructive tests (such as the F.W.D. tests) thicknesses measurements of the various pavement layers, utilizing remote sensing techniques such as the radar technique. Thus, the main goal of this research was to establish reliable procedures by which the radar technique could be used for the required thickness determination. The research approach was characterized by both theoretical and empirical aspects in order (a) to formulate the basic principles and equations for calculating the various types of errors associated with radar measurements, (b) to identify the radar waveform feature that best correlates with the various layer thicknesses and (c) to develop the most appropriate testing procedures for the radar technology including both calibration and routine tests.

Accomplishments/Products

Project accomplishments included:

(a) A theoretical literature survey in order to formulate the basic principles that govern the various radar system operations.

(b) Formulation of the basic principles and equations for calculating the various types of errors associated with radar measurements were formulated.

(c) Laboratory and in-situ radar tests in order to study their accuracy as well as the accuracy of past predictions of the flexible pavement's various layers.

(d) The conduct of routine radar tests in three sites under the full cooperation of the Massachusetts Department of Public Works (MDPW) were conducted.

Publications

Livneh, Moshe, Siddiqui, M.S., "Assessment of Radar Technology for Determining the Thickness of Pavement Layers," August 1990, CCRE/PACT Report # 91-7.

Research Assistant

Siddiqui, Mohammed, "Assessment of Radar Technology for Determining the Thickness of Pavement Layers," SMCE 9/90.

9. <u>An Alternative Conceptualization: Infrastructure Systems as Ill-Defined Systems</u>

Principal Investigator: **Dr. Frannie Humplick**

Description of Project: Holistic representations of infrastructure systems are used to develop maintenance management systems, outline long-term policies, and conduct long term impact studies. Representations of this nature require combining elements of knowledge from diverse sources which are independently developed. Because of the manner in which these representations are developed it is contested that they are "ill-defined". The objective of this research is to develop a methodology that allows systematic construction and updating of holistic infrastructure representations that recognizes "ill-definedness". The approach adopted is the meta-modeling of representations. A representation is analyzed according to its:

(i) structural performance which captures the large number of interactions between components making up infrastructure;

(ii) technological performance which captures the flow of data, information, intelligence, and decision-making rationales; and

(iii) behavioral performance which captures the trend of infrastructure towards satisfying functional requirements.

A measure of the performance of a representation is developed and used to define the stage at which "ill-definedness" creeps into a representation.

Accomplishments/Products

Key accomplishments in this exploratory project included:

- Analytical derivation of a performance measure of a representation from a structural, technological, and behavioral point of view;

- Explicit inclusion of the degree of ill-definedness of a representation in the measure of performance. The feasibility of such an approach to representing infrastructure systems was tested on a case study capturing the effect of ranges in decision-response such as extremely responsive, totally unresponsive, periodic response, and random response on the "physical state" of infrastructure.

Publications

Humplick, F.: "An Alternate Approach to Measurement Error Modeling", Forthcoming in Transportation Research B.

Humplick, F. and Ben-Akiva, M., "A Methodology for Estimating the Accuracy of Inspection Systems," working paper presented at ORSA, Philadelphia, October, 1990.

Ben-Akiva, M., Humplick, F., Madanat, S., and Ramaswamy, R., "The Latent Performance Approach to Infrastructure Management" Paper under review for publication by the ASCE Journal of Transportation, and to be presented at the 70th Annual Meeting of the Transportation Research Board, Washington D.C., January 13-17, 1991.

Humplick, F., and Moavenzadeh, F. "Infrastructure as an Ill-Defined System: A Meta-Analytic Representation", Working Paper, Center for Construction Research and Education, Department of Civil Engineering, MIT, July, 1990.

2. TECHNOLOGY ASSESSMENT

A. INNOVATION/DIFFUSION

1. Development of Methods for Exploring, Synthesizing and Implementing Advanced Construction Systems

Principal Investigator: **Professor Carl R.Peterson**

Description of Project: Construction is a complex process, served by a fragmented, sometimes even competing, community of owners, designers, manufacturers, and contractors. Opportunities for substantial advances in construction technology almost invariably reach across traditional industry boundaries. Opportunities are difficult to recognize and even more difficult to explore. Mechanisms to synthesize and commercially implement necessarily interdisciplinary advanced systems are virtually absent. In this project, formal design methods were explored as a means to organize interdisciplinary thinking, to facilitate communication, to document and justify design decisions, to quantify and compare options, and to stimulate the generation of new and hybrid methods and materials. New methods were proposed for realistically treating segmented construction activities ranging from determination of owner needs, through design, to actual construction.

Accomplishments/Products

Many design "Methodologies" were reviewed, particularly in the field of mechanical design, together with, formal planning, scheduling, and monitoring techniques commonly employed in construction projects. Of the design "methodologies", the Pugh Concept Selection System was found to be best suited to the task in terms of flexibility, ease of application, and ability to stimulate new and hybrid concepts in innovative design. However, it has been developed around typical manufacturing applications, where owner, designer, fabricator and user (or marketer) are one and the same. The method's suitability for design/construction applications was tested in a preliminary way in a search for advanced concepts for construction of an ordinary garage. This test produced concepts for an expanded design process that provided for rapid and

convenient communication, and a formal means to recognize and document conflicts so that they could be resolved at an early stage. The work reached an appreciation of total scope and outlined a core effort that could provide a framework for the coordination of a variety of research projects. The project developed, refined, and tested an appropriately partitioned, cooperative design procedure for relatively simple projects, such as a small office building. The procedure was tested in the fall of 1990 in a special interdepartmental subject "Multi-Disciplinary Design for Fragmented Industries".

PACT Fellow/Thesis

Pflueger, John C., "A Design Method for Cross-Disciplinary Coordination and Innovation," Ph.D. 5/91

2. **Sources of Innovation in the Construction Industry and Implications for Construction Industry Innovation Management**

Principal Investigator: **Professor Eric VonHippel**

Description of Project: Studies of innovation carried out over the last few years have shown that the sources of innovation vary greatly. In some fields, innovation users develop most innovations. In others, suppliers of innovation-related components and materials are the typical sources of innovation. In this study, the goal was to identify and learn to manage the sources of innovation in the construction industry through observation of innovation patterns in the construction industry and analysis of innovation management patterns.

Accomplishments/Products

The research compiled samples of important innovations that have been adopted in the field of residential construction in the post-WWII period. The classes of innovation studied include framing systems, wall systems, plumbing systems, etc. The sources of the many innovations were identified and studied including user, manufacturer, and supplier. While the sources of many innovations were determinable, data on the sources of others were not retrievable. The data collection in this project illustrated that many innovations important to the construction industry

are developed by those who use them (the builders) rather than by product manufacturers or material suppliers.

PACT Fellow/Thesis

Slaughter, E. Sarah, "Rapid Innovation and Integration of Components: Comparison of User and Manufacturer Innovations Through a Study of Residential Construction." CCRE/PACT Report # 91-3.

3. Transfer of Technical Information in the Construction Industry

Principal Investigator: **Prof. Stephan Schrader**

Description of Project: Identify areas with potential for improving the horizontal and vertical technology transfer within the US construction industry through an in-depth study of one specific industry segment (wood windows manufacturing).

Method: Field study, interviews.

Outcome:
- Description of technological change in window manufacturing
- Identified sources of technical information in this industry segment
- Described information transfer patterns.

Publications

"Information Transfer within the Window Industry." Year End Project Report. Submitted to the MIT Center for Construction Research and Education, Program for Advanced Construction Technology, January 1990.

B. PRODUCTIVITY AND COMPETITIVENESS

1. Advanced Ceramics in Construction

Principal Investigator: **Mr. Michael Markow**

Description of Project: In the past several years advances in materials science and engineering have produced exotic, high-performance ceramics that have been applied in such diverse fields as electronics, machine tools, wear components, coatings, armor, magnets, and replacements for bone and teeth. These wide-ranging and

growing applications result from the very desirable properties of advanced ceramics, including high (compressive) strength, resistance to wear and corrosion, tolerance of temperature extremes, and ability to exhibit different electrical, magnetic, mechanical, and optical properties.

New materials such as advanced ceramics could help provide the technological basis for improvements in the productivity, quality, cost, and capability of the U.S. construction industry. although the initial costs of advanced ceramics are higher than those of conventional construction materials, these costs may be justified by the superior performance and improvements of current construction practices that advanced ceramics may promote, the life-cycle benefits of improved facility performance (which may more than offset initially higher costs), and the need for such materials in unique, demanding, and very specialized facilities and applications. The objective of this project is to identify and analyze the potential applications of advanced ceramics in construction.

Accomplishments/Products

The research results include: a survey of the status and direction of research and developments in advanced ceramics and ceramic composites; a survey of current trends in conventional materials usage in construction; the identification of example facilities, applications, and processes in construction where ceramics would be good candidates for introduction; analysis of the potential impacts of ceramics on facility performance and life-cycle costs and benefits; and conclusions as to the roles that ceramics might be expected to play in construction, their technical and economic advantages and disadvantages, new markets and possibilities posed by the unique characteristics of ceramics (whether existing or promised), and recommendations of areas for further investigation.

Publications

Markow, Michael J. Brach, and Brach, Ann M., "Advanced Ceramics in Construction," Final Report, December 1987, CCRE/PACT Report # 87-25

Research Assistant/Thesis

Brach, Ann M., "The Potential for Advanced Ceramic Materials in Construction," SMCE 5/87.

2. **Technology Evaluation to Improve the Effectiveness of Innovation**

Principal Investigator: **Dr. Alice Amsden**

Description of Project: Given the limited resources an institution may devote to R&D, the question arises as to how to improve the decision-making process regarding which R&D projects to continue funding and which to terminate. Using CAD as an example, this project attempts to develop a methodology to enable institutions to make the best decisions.

Accomplishments/Products

A framework of a method has been developed to compare new projects to earlier generations in the same family with respect to costs and quality (performance). This framework is designed to judge whether a project is (i) highly original and an improvement on existing technology; and (II) cost effective. Data from several generations of CAD are being collected to develop and test the methodology.

Publications

Amsden, Alice H. and Bar-Or, Emanuel, "Technology Evaluation Methodology: The Examples of CADD and Roofing Systems," CCRE/PACT Report # 90-5.

EXHIBIT H
CCRE/PACT PUBLICATIONS

NUMBER	TITLE	AUTHOR
	1983	
83-1	Life Cycle Pavement Cost Allocation	Michael J. Markow Thomas Wong
83-2	Planning and Management Alternatives in the Rehabilitation of a National Railroad System	Michael J. Markow
83-3	Overcoming Fleet Capacity Constraints in Developing Countries: Analysis of Investment and Maintenance Options	Fred Moavenzadeh Michael J. Markow Brian D. Brademeyer
83-4	A Methodology for Intercity Transportation Planning in Egypt	Fred Moavenzadeh Michael J. Markow Brian Brademeyer Nabil Safwat
83-5	Estimating Road Construction Costs in Developing Countries	Michael J. Markow
83-6	The Infrastructure Crisis-Summary of a Series of Roundtable Discussions Sponsored by CCRE, Touche Ross, and Prudential Bache	
83-7	Global Prospects for Concrete Construction	Fred Moavenzadeh
83-8	Construction and Building Materials Industries in Developing Countries	Fred Moavenzadeh Frances Hagopian
83-9	Reorganization in Departments of Public Works	Henry Irwig
83-10	Computer-Based Information Systems (CBIS) in Construction Firms: Organization Aspects	Henry Irwig William Reinhardt
83-11	Research Projects in Construction	CCRE
83-12	Evaluation of Project Management and Control Procedures Used by the Florida Dept. of Transportation	Robert D. Logcher Henry Irwig
83-13	Indices and Abstracts of Theses for the Construction Engineering and Management Program: September 1980-June 1983	CCRE

*Denotes report from the Program for Advanced Construction Technology (PACT)

83-14	Feasibility of Gypsum Quarrying and Gypsum Based Construction Product Manufacturing in Egypt	Fred Moavenzadeh Charles H. Helliwell
83-15	International Construction Financing	Fred Moavenzadeh Alex Demacopoulos
83-16	Planning for the Expansion of Regional Water Supply Systems	David H. Marks
83-17	Micro-Computer Software and Hardware Technology Strategies	David H. Marks
83-18	Decision Support Systems for Infrastructure Maintenance and Rehabilitation	David H. Marks
83-19	The Impact of Owner-Engineer Risk Sharing on Design Conservation	R.E. Levitt N.H. Qaddami Robert D. Logcher
83-20	The Demand for Freight Transportation: Methods and Applications	Clifford Winston
83-21	Conceptual Developments in the Economics of Transportation: An Interpretive Survey	Clifford Winston
83-22	An Econometric Analysis of the Demand for Intercity Passenger Transportation	Clifford Winston S. Morrison

1984

84-1	Progress Report	CCRE
84-2	The RENFE-MIT Collaborative Rail Research Program Final Report for Phase Two	RENFE/MIT
84-3	Problems in Designing Pre-stressed Segmental Concrete Bridges	Daniel J.W. Wium Oral Buyukozturk
84-4	Evaluation of Design and Performance Porter Square Transit Station Chamber Lining	Herbert H. Einstein Amr S. Azzouz
84-5	Comparison of Five Empirical Tunnel Classification Methods Accuracy, Effect of Subjectivity and Available Information	Herbert H. Einstein David E. Thompson Amr S. Azzouz
84-6	Micro-Computer Packages for Construction Management	Massimo Grimaldi Robert D. Logcher David H. Marks

84-7	The Effect of Cyclical Construction Demand on the Operational Firms in Cyclical Economic Environments	Thomas K. Wong Robert D. Logcher
84-8	The Operation and Performance of Construction Firms in Cyclical Economic Environments	Thomas K. Wong Robert D. Logcher
84-9	Precast Segmental Bridges Status and Future Directions	Daniel J.W. Wium
84-10	Application of Artificial Intelligence to Problems of Rock Mechanics	William S. Dershowtiz
84-11	Intelligence for Construction Robots	Gregory B. Baecher
84-12	Indices and Abstracts of Theses for Construction Engineering and Management Program: September 1983-June 1984	CCRE
84-13	Research Projects in Construction	CCRE
84-14	The Construction Industry in Egypt	Fred Moavenzadeh Tarek Selim
84-15	A State-of-the-Art Study of Non-Convective Solar Ponds for Power Generation	A.D. Carmichael
84-16	Computer Simulation to Address Issues of Public Policy	Michael J. Markow
84-17	Planning and Management Alternatives in Rehabilitation of a National Rail System	Michael J. Markow

1985

85-1	CCRE 1984 Annual Report	CCRE
85-2	An Expert Systems Framework for Analyzing Construction Project Project Risks	Leston Nay Robert Logcher
85-3	The Building Materials Industry in Developing Countries: An Analytical Appraisal	Fred Moavenzadeh
85-4	Research Needs in Transportation Facilities: Guideway Technology Materials and Research	Fred Moavenzadeh
85-5	Detection of Leakage Through Subsurface Barriers Using Guided Acoustic Wav	K.R. Maser M.N. Toksoz

85-6	IMST User's Manual	D. NavinChandra
85-7	International Construction Financing	Alex Demacopoulos Fred Moavenzadeh
85-8	Intelligent Use of Constraints for Activity Scheduling	D. NavinChandra

1986

86-1	CCRE Annual Report 1985	CCRE
86-2	Physical Measurements for Evaluation of Lock Gate Condition	Richard Littlefield Kenneth Maser Jack R. Kayser
86-3	ESCUPAD: Initial Knowledge-Based System for Processing Queries to CAPCES	Robert D. Logcher Ayman Hindy Ming-Teh Wang
86-4	Thermal Modelling of a Leaky Roof	Udaya Halabe
86-5	Analysis of Concrete Deterioration Using Ground-Penetrating Radar	Kenneth R. Maser
86-6	Management System for Repair Evaluation, Maintenance and Rehabilitation of Civil Works Interim Report	Michael J. Markow
86-7	Evaluation of Underground Liners and Barriers Using Guided Seismic Waves	Kenneth R. Maser
86-8	Management System for Repair Evaluation, Maintenance and Rehabilitation of Civil Works Final Report	Michael J. Markow
86-8(A)	Decision Support System for Tunneling	Herbert Einstein Y.W. Kim Robert Logcher
86-9	Research Report to be Conducted by N.E. Surface Transportation Consortium	Thomas F. Humphrey
86-9(A)	SIMSUPER5: Tunneling Construction Simulation	Herbert Einstein G.F. Salazar
86-10	Application of a Three-Dimensional Coupled Finite Element-Boundary Element Method	Herbert Einstein R. Ushijima

86-11	Fracture Resistance Parameters and Their Experimental Determination	Victor Li
86-12	Fracture Processes in Concrete and Fiber-Reinforced Cementitious Composites	Victor Li E. Liang
86-13	Automation of Condition and Deterioration Surveys Using Knowledge-Based Signal Processing	K. Maser D. Smit
86-14	Detection of Progressive Deterioration in Bridge Decks Using Ground-Penetration Radar	K. Maser
86-15	Infrastructure Challenges in Construction Research	F. Moavenzadeh
86-16	Construction Industry, Supplier of Housing	F. Moavenzadeh
86-17	Private Highways: A Proposal to Help Resolve the Highway Infrastructure Crisis	F. Moavenzadeh
86-18	U.S. Construction Industry	F. Moavenzadeh
86-19	Transportation Technology Choice and Energy Consumption in Egypt	F. Moavenzadeh
86-20	The Economic Argument for Highway Ownership Privatization	F. Moavenzadeh D. Geltner
86-21	Potential Applications of Artificial Intelligence in Civil Engineering	F. Moavenzadeh
86-22	Construction High-Technology Revolution	F. Moavenzadeh

1987

87-1	Annual Report for 1986	CCRE
87-2	CAPES Knowledge-Base Documentation: A Cafeteria Architectural Planning Expert System	Robert D. Logcher John N. Ivan Patrick A. Purcell
87-3	CAPES Users Manual A Cafeteria Architectural Planning Expert System	Robert D. Logcher John N. Ivan Patrick A. Purcell Erik Borne

87-4	CAPES Users Manual: A Cafeteria Architectural Planning Expert System	Robert D. Logcher John N. Ivan Patrick A. Purcell Erik Borne
87-5	Use and Interpretation of High Speed Sensors in the Diagnosis of Flexible Pavement Systems	Richard B. Littlefield
87-6	Expert-MCA: A Knowledge-Based Natural Language Interface II CAPCES Database	Ayman Hindy Robert Logcher MinTang Wang
87-7*	Failure Mode Maps for Foam-Core Sandwich Beams	Thanasis C. Triantafillou Lorna J. Gibson
87-8*	Minimum Weight Design of Foam Core Sandwich Panels for a Given Strength	Thanasis C. Triantafillou Lorna J. Gibson
87-9*	Construction Automation Research at MIT	Alexander H. Slocum Laura Demsetz David Levy Bruce Schena Andrew Ziegler
87-10	Adding Knowledge-Based Systems Technology to Project Control Systems	Robert D. Logcher
87-11*	Application of Automated Interpretation to Sensor Data	Kenneth R. Maser
87-12	The Economic Optimization of Pavement Maintenance and Rehabilitation Policy	Michael J. Markow Brian D. Brademeyer James Sherwood William J. Kenis
87-13	Demand Responsive Approach to Highway Maintenance and Rehabilitation-Executive Summary	Michael J. Markow
87-14	Demand Responsive Approach to Highway Maintenance and Rehabilitation, Volume I: Development of Concepts & Examples	Michael J. Markow
87-15	Demand Responsive Approach to Highway Maintenance and Rehabilitation:Volume II: Optimal Investment Policies for Maintenance and Rehabilitation	Michael J. Markow
87-16	Demand Responsive Approach to Highway Maintenance, Volume III: Applications to Pavement Type Selection and Alternate Bidding	Michael J. Markow

87-17	The U.S. Construction Industry Summary of Testimony Before U.S. House of Representatives SubCommittee on Science, Research and Technology	Fred Moavenzadeh
87-18	Building Materials: An Overview Reprint from "Encyclopedia of Materials Science and Engineering	Fred Moavenzadeh
87-19	Automated Interpretation of Sensing In-Situ Conditions	Kenneth R. Maser
87-20	Application of Radar and Infrared Thermography to Inspection of Bridge Decks	Kenneth R. Maser
87-21	Leak Detection in Large Storage Tanks Using Seismic Bounding Waves	S. Modanat U Halabe Kenneth R. Maser
87-22	Sensors for Infrastructure Assessment	Kenneth R. Maser
87-23	Inventory, Condition and Performance Assessment in Infrastructure Facilities Management	Kenneth R. Maser
87-24	Pavement Condition Diagnosis Based on Multisensor Data	Kenneth R. Maser Brian D. Brademeyer Richard Littlefield
87-25*	Advanced Ceramics in Construction	Michael J. Markow Ann M. Brach
87-26*	Fiber Reinforced Structural Ceramics for Construction	Victor C. Li Christopher K.Y. Leung
87-27*	Optimum Design Methods for Sandwich Panels	Lorna J. Gibson
87-28*	Design Methodology for Automated Construction Machines	Alexander H. Slocum Laura Demsetz David Levy Bruce Schena
87-29*	An Object-Oriented Programming Environment for Communication Coordination and Control in Computer Integrated Design and Construction	D. Sriram R.D. Logcher N. Groleau
87-30*	Mechanics of Damage in Rate Sensitive Construction Materials	S. Shyam Sunder Mao S. Wu
87-31*	The Role of Uncertainty in the Management of Infrastructure Facilities	Sue McNeil Frannie Humplick

87-32*	Assessment of In-Situ Conditions Using Wave Propagation Techniques	Kenneth R. Maser

1988

88-1	Annual Report for 1987	
88-2	Expert-MCA: An Expert System for CAPCES Databases	Robert D. Logcher Frank Hsi-Sheng Chen M. Wang
88-3	Potential Application of Artificial Intelligence in Pavement Maintenance Management	Fred Moavenzadeh Brian Brademeyer
88-4*	Blockbot: A Robot to Automate Construction of Cement Block Walls	Alexander Slocum Bruce Schena
88-5*	Ceramics for Construction	Victor C. Li Christopher K.Y. Leung
88-6	Design Considerations for Ultra Precision Magnetic Bearing Supported Slides	Alexander Slocum David b. Eisenhaure
88-7	Construction: The Foundation of National Defense	Gregg F. Martin
88-8	Option Valuation of Claims on Real Assets: The Case of Offshore Petroleum Leases	James Paddock Daniel R. Siegel James L. Smith
88-9*	Virtual Construction	Alex Pentland John Williams
88-10	Support for a Firing Range Placement Module for Army Installation Planners	Robert D. Logcher
88-11	Design of a Deployable Collapsible Prototype for Mid-Sized Shelters	Robert D. Logcher Y. Rosenfeld
88-12	Developing New Concepts and Design Procedures for Flat Deployable Structures	Robert Logcher Y. Rosenfeld
88-13*	Automated Construction of Partition Wall Framework	Laura Demsetz
88-14*	Program for Advanced Construction Technology at MIT	CCRE
88-15	Research and Development in the U.S. Construction Industry	Fred Moavenzadeh Ann Brach

1989

89-1	Growth, Development and Competitiveness of Korean Construction Industry	Kang Sik Park
89-2	A Strategic Response to a Changing Engineering and Construction Market	Fred Moavenzadeh
89-3	Presence of Foreign Firms in U.S. Engineering and Construction Market	Fred Moavenzadeh
89-4*	Propagation Characteristics of Electromagnetic Waves in Concrete	Udaya B. Halabe Kenneth Maser Eduardo Kausel
89-5*	DICE: An Object-Oriented Programming Environment for Cooperative Engineering Design	S. Sriram R. Logcher N. Groleau J. Cherneff
89-6*	Optimum Design Methods for Structural Sandwich Panels	Lorna J. Gibson
89-7*	Fiber Reinforced Structural Ceramics for Construction	Victor C. Li Chris Leung
89-8*	Debonding in Foam-Core Sandwich Panels	Lorna J. Gibson T.C. Triantafillou
89-9*	An Automated Shear Stud Welding System	Alex H. Slocum Andrew Ziegler
89-10*	Automatic Construction System	R. Logcher Jonathan Cherneff Duvvuru Sriram
89-11*	Good Vibrations: Modal Dynamics for Graphics and Animation	Alex Pentland John Williams
89-12*	Interactive Integrated Design Visualization of Foam and Process	John Williams Alex Pentland Jerome Connor
89-13*	Fast Simulation on Small Computers Modal Dynamics Applied to Volumetric Models	Alex Pentland John Williams
89-14*	The Use of Models for Foam Core Behavior in the Design of Sandwich Panels	Lorna J. Gibson
89-15*	Object Representation and Dynamics of Multi-Body Structures	John Williams Alex Pentland
89-16*	Task Identification for Construction Automation	Laura Demsetz

89-17*	Virtual Manufacturing	Alex Pentland John Williams
89-18*	Object Representation for Design, Unifying Cubes and Spheres	Alex Pentland John Williams
89-19*	Animation and Physical Modeling Strategies for Design	Alex Pentland John Williams
89-20*	Superquadrics and Modal Dynamics for Discrete Elements in Concurrent Design	Alex Pentland John Williams
89-21*	Perception of Non-Rigid Motion: Inference of Shape Materials and Force	Alex Pentland John Williams
89-22*	Creep of Polymer Foams	J.S. Huang Lorna J. Gibson
89-23*	Creep of Sandwich Beams with Polymer Foam Cores	J.S. Huang Lorna J. Gibson
89-24*	First Cracking Strength of Short-Fiber Reinforced Ceramics	C.K. Leung Victor C. Li
89-25*	Estimation of Latent Pavement Performance from Damage Measurements	M. Ben-Akiva R. Ramaswamy
89-26*	Application of a Two-Way Debonding Theory to Short Fiber Composites	C.K. Leung V.C. Li
89-27*	A New Strength-Based Model for the Debonding of Discontinuous Fibers in an Elastic Matrix	C.K. Leung V.C. Li
89-28*	Strength-Based and Fracture Based Approaches in the Analysis of Fiber Debonding	C.K. Leung V.C. Li

1990

90-1*	High Performance Simulation	Alex Pentland John Williams
90-2*	Coupling Physical Simulation and CAD	Alex Pentland John Williams
90-3*	Object Oriented Discrete Elements	Alex Pentland John Williams
90-4*	Inferring Materials Properties	Alex Pentland John Williams

90-5*	Technology Evaluation Methodology The Examples of CADD and Roofing Systems	Alice H. Amsden Emanuel Bar-Or
90-6*	Development of Methods for Exploration, Synthesis, and Imple-metation of Advanced Construction System	Carl R. Peterson
90-7*	The Thing World Modeling System: Virtual Sculpting by Modal Forces	Alex Pentland A. Essa I. Friedmann M. Horowitz B. Sclaroff
90-8*	Computational Complexity Versus Simulated Environments	Alex Pentland
90-9*	A Strategy for Construction-Oriented Design	Jerome Connor L. Albano
90-10*	Computer-Based Methodology for Integration of Design and Construction	Jerome Connor L. Albano
90-11*	Segmentation Algorithms for Pave-ment Images	Haris Koutsopoulos
90-12*	Methods and Algorithms for Auto-mated Analysis of Pavement Images	Haris Koutsopoulos I.El Sanhouri
90-13*	Analysis of Segmentation Algorithms for Pavement Distress Images	Haris Koutsopoulos I. El Sanhouri A. Downey
90-14*	Application of Statistical Pattern Recognition to the Identification of Pavement Distresses	Allen B. Downey
90-15*	A Methodology for Estimating the Accuracy of Inspection Systems	Frannie Humplick Moshe Ben-Akiva
90-16*	Computer-Based Segmentation and Interpretation of Pavement Surface Distress Images	Ibrahim El Sanhouri
90-17*	Strengthening of R/C Beams with Epoxy-Bonded Fiber Composite Materials	Thanasis C. Triantafillou Nikolaos Plevris
90-18*	FRP-Reinforced Wood as Structural Material	Nilolaos Plevris Thanasis C. Triantafillou

1991

91-1*	Mechanical Behavior of Cementitious Foams	Tonyan, Timothy D.
91-2*	An Innovative Technology in Concrete Construction: Semi-Automated Rebar Tying	Altobelli, Frank R.
91-3*	"Rapid" Innovation and Integration of Components: Comparison of User and Manufacturer Innovations Through a Study of Residential Construction	Slaughter, Elisabeth S.
91-4*	A Design Method for Cross-Disciplinary Coordination and Innovation	Pflueger, John C.
91-5*	Materials Selection for Sandwich Panels in Housing Construction	Tonyan, Timothy D. Gibson, Lorna J.
91-6*	Construction Automation: Basic Table Selection and Development of the Cranium	Everett, John G.
91-7*	Assessment of Radar Technology for Determining the Thicknesses of Pavement Layers	Moshe Livneh Mohammad Sivdiqui
91-8*	Contectual Knowledge and the Diffusion of Technology in Construction	Ann M. Brach
91-9*	Strategic Flexibility Real Options, and Product-Based Strategy	Ronald. A. Sanchez
91-10*	A Design Methodology for Deployable Structures	Charis Gantes Jerome Connor Robert Logcher
91-11*	Fracture Toughness of Brittle Honeycombs	J.S. Hung Lorna Gibson
91-12*	Fracture Toughness of Brittle Foams	J.S. Hung Lorna Gibson
91-13*	Optimum Cell Size and Density of Brittle Foams for a Given Compressive Strength and Fracture Toughness	J.S. Hung Lorna J. Gibson
91-14*	Materials and Cross Sectional Shapes for Bending Stiffness	J.S.Hung Lorna J.Gibson
91-15*	Elastic Moduli of a Composite of Hollow Spheres in a Matrix	J.S.Hung Lorna J. Gibson
91-16*	A New Strength Based Model for Debonding of Discontinuous Fibers in an Elastic Matrix	Christopher Leung Victor Li

91-17*	Effect of Fiber Inclination on Crack Binding Stress in Brittle Fiber Reinforced Matrix Composites	Christopher Leung Victor LI
91-18*	Steady State And Multiple Cracking of Short Random Fiber Composites	Christopher Leung Victor Li
91-19*	A Fracture Based Two Way Debonding Model for Discontinuous Fibers in and Elastic Matrix	Christopher Leung
91-20*	Failure Initiation in EPDM Lap Joints in a Lap Shear Test	S.Shyam Sunder C. Lakshaman Rao, Jerome Connor
91-21*	Characterization of Bulk Property of Butyl Adhesives	Sunder Connor Lakshaman
91-22*	Shear Deformations in Adhesively Bonded Elastomeric Lap Joints	S.Shyam Sunder C. Lakshaman Rao Jerome Connor
91-23*	Measurement and Interpretation of Reinforcement Stresses in the APSR Cell	A. J. Whittle J. T. Germaine Larson Abermento
91-24*	Shear Lag Analysis of A Planar Soil Reinforcement in Plane Strain Compression	Andrew Whittle Marucio Amermento
91-25*	Strengthening and Or Reinforcing Structures with Fiber Reinforced Plastic Composites	Nikolaos Plevris
91-26*	Post Strengthening of R/C Beams with Apoxy Bonded Fiber Reinforced Materials Note* Included in 91-25	Triantifillou Plevris
91-27*	A Primitive Based Approach To the Classification of Pavement Distressed Images	Haris Koutsopoulos
91-28*	Methods and Algorithms for Automated Analysis of Payment Images	Ibrahim El-Sanhouri Haris Koutsopoulos
91-29*	Automated Analysis of Pavement Distress Data	Haris Koutsopoulos Rabi Mishalani Allen Downey
91-30*	An Approach for Predicting Latent Infrastructure Facility Deterioration	Rohit Ramaswamy Moshe Ben-Akiva
91-31*	Infrastructure Management Under Uncertainty the Latent Performance Approach	Frannie Humplick Moshe Ben-Akiva Samir Madanat Robit Ramaswamy
91-32*	A New Theory for the Debonding of Discontinuous Fibers in an Elastric Matrix	Victor Li Christopher Leung

91-33	Good Vibrations Modal Dynamics for Graphics and Animation	John Williams Alex Pentland
91-34	The Latent Performance Approach to Infrastructure Management	Frannie Humplick Moshe Ben-Akiva Samir Madanat Robit Ramaswamy

1992

92-1*	The Hazardous Waste Remedation Market: Innovative Technological Development, and The Market Entry of the Construction Industry	Hoffman, Andrew J.
92-2	Graduate Student Theses	CCRE
92-3*	Strengthening of Cement Foams	Lorna J. Gibson Timothy D. Tonyan
92-4*	Structure and Mechanics of Cement Foams	Lorna J. Gibson Timothy D. Tonyan
92-5*	Advanced Fiber-Reinforced Polymer Composites as External Reinforcement of Long-Term Behavior	Nikolaos Plevris Thanasis C. Triantafilou
92-6*	Solid Waste Management: Decision and Market Dilemmas	Henry F. Taylor III
92-7*	Executive Education Programs in the Construction Industry: An Analysis of Existing National Programs and Current Industry Participation	Susan Ann Tomlinson-Dykens
92-8*	Modeling Infrastructure Performance and User Costs	Dinesh A. Gopinath
92-9*	Deformation and Failure of Adhesively Bonded Elastometric Lap Joints	Chebolu Lakshmana Rao
92-10*	Modelling and Seismic Imaging of Buried Structures	Antonio Jose Barreto Tadeu
92-11*	An Axiomatic Approach to Performance-Based Design	Leonard Albano
92-12*	A Survey of the Environmental Construction Market	Edmund S. Pendleton
92-13	Turning "Green" Organizational Change in the Army Corps of Engineers, 1962-1991	Gregg F. Martin
92-14	Knowledge Acquistion in Conceptual Project Scheduling	Erik Gustaf Eino Swenson

92-15	Construction Industry Organization, Labor Relations and Productivity	Frederick L. Blanchard
92-16	Contract Administration of Department of Defense Environmental Restoration Contracts	John H. Edwards
92-17	Strategic Business Planning for the Minority Contractor	Pamela Lynn Shelton Botman
92-18	Customer Service Quality Management in the Construction Industry: A Comparative Study of the U.S. and Japan	Tatsuhiko Asahara
92-19	The U.S. Army Corps of Engineers' Role in Reconstruction of Kuwait: A Case Study and Its Implications for Future International Missions	Brian L. Baker
92-20	Privatization and Its Role in the Reconstruction of Lebanon	Sami A. Boustany
92-21*	Micromechanical Modeling of Ductile-Fiber-Reinforced Ceramics	Jeffrey C. Chi
92-22	Core Competencies and Skills-Based Competition Among General Contractors	Joseph Gioioso
92-23	Constructed Wetlands: A Growing Opportunity for the Construction Industry	Kevin L. Griffith
92-24	Analysis of Information Flow of Facility Management in a Japanese General Contractor with Focus on HVAC Systems	Ken Hatano
92-25	Potential of Strategic Information Systems for Japanese Construction Firms	Hisashi Inagawa
92-26	Optimal Design of Fendering System for Marine Pier	Kok-Hwa Law
92-27	Repair Versus Development in the Reconstruction of Lebanon: A Case Study of the Metropolitan Beirut Water Supply System	Adel B. Mardelli
92-28	Strategic Information System for Standardized Buildng Business	Tatsuhiko Natsuhara
92-29	Financial, Organizational and Technology Strategies for Wastewater Treatment Projects in Small and Medium-Size Coastal Municipalities in Greece	Haralabos N. Pandis
92-30	Communication and Information in the Building Process	Roberto Pietroforte

92-31	The Department of Defense and the Construction Industry: Leadership Opportunities in Hazardous Waste Remediation Innovation	Michael A. Rossi
92-32	Alternative Contracting Methods in the U.S. Army Corps of Engineers	Craig L. Simoneau
92-33	The Role of R&D in Construction Firms	Satoshi Someya
92-34	Exploring the Municipal Solid Waste Recycling Option: The Case of Sao Paulo, Brazil	Jacks Sterenfeld
92-35	Multiobjective Structural Design for Constructable Facilities	Ali Tobah
92-36	Real Options and Affordable Alternatives: A Contingent Claims Approach to the Economics of Ownership	Yaniv Tepper
92-37*	A Laboratory Investigation of Load Transfer in Reinforced Soil	Douglas Gregory Larson
92-38*	Solid Waste Management: Opportunities for Market Entry by the Construction Industry	Henry F. Taylor
92-39	A Survey of the Environmental Construction Market	Edmund S. Pendleton
92-40	The Department of Defense and Hazardous Waste Remediation	Edmund S. Pendleton
92-41*	Finite Element Assessment of Cracks and Delaminations in Concrete Bridge Decks by the Impact-Echo Method	Yiping Geng
92-42*	Classification Methods for Pavement Distress Images	Vassilios I. Kapotis

1993

93-1	The Spanish Construction Opportunities and Challenges Beyond 1992	Luis Miguel Dominguez Higuera
93-2	Diffusion of Innovation in the Construction Industry: High Strength Concrete	Laurent Combier
93-3	Competitive Strategies for Korean Construction Firms for Changing Circumstances	Jongmin Hong
93-4	The Public Sector Construction Industry: Analysis of Single-Project Partnering	Peter W. Mueller
93-5	Water for Life: Fighting Water Pollution in Eastern Europe	Walter C. Frey
93-6	Shear Behavior of Fiber Reinforced High Strength Concrete Beams	Amjad Shahbazker

93-7	Feasibility of Privatization of Expressway in Japan	Matsui, Yasuyuki
93-8*	High Performance MAGLEV Guideway Design	R. Scott Phelan
93-9	Quality Cost Models for Construction Firms: A Strategic Information System Approach	Ching-Liang Wu
93-10	Contracting Methods and Management Systems of Remedial Action Contracts Within the U.S. Navy's Installation Restoration Program	Banaji, Darius
93-11	An Evaluation of the North American Free Trade Agreement and Its Effects on the Mexican Construction Industry	Benitez Malvido, Pedro Luis
93-12	A Study of Section 936 of the Federal Internal Revenue Code and Its Impact on Puerto Rico's Construction Indusry	Casanova Tirado, Pedro Rafael
93-13*	Atmospheric Emissions: Opportunities for the Construction Industry in Electric Power Stations	Cauchy, Nicolas
93-14*	The Developing Environment: An Investigation of Democratic Values, Environmental Trends and Implications for Development (A Case Study of Columbia, Missouri)	Crews, Daniel O.
93-15	Quantity Surveys from Shared CAD Object Models: A Development Strategy	Edwards, Andrew E.
93-16	Deforestation: Policies Toward a More Sustainable Tropical Timber Industry	Griffith, Jennifer Lynn
93-17	Episodic Patterns in the Introduction of New Technologies: AEC Firms in the US and Japan	Ho, Kiam Khiaw
93-18*	Sustainable Development, Infrastructure and Environmental Investment and the Privatization Decision	Liddle, Brantley T

1994

94-1	Graduate Student Theses 1983-1994	
94-2	Strategies of the Major Spanish Construction Companies for Improving Their Domestic and International Competitivness	Gomez Barquin, Gonzalo
94-3	Financing Infrastructure Development in Mexico Through Public-Private Partnerships: The Huites Hydroelectric Dam	Jinich Ganez, Roberto
94-4	A Study of Section 936 of the Federal Internal Revenue Code and Its Impact on Puerto Rico's Construction Industry	Casanova Tirado, Pedro Rafael
94-5	Accelerated Methods of Residential Construction Prefabrication Re-Evaluated	Richman, Judah Lee

94-6	The Economic Impacts on Green Product Development	Chen, Jeff Yen-Chou
94-7*	How Environmental Considerations Are Changing The Construction Industry: Five Technologies for Lower Energy Demand and Decreased Air Emissions	Steele, Matthew W.
94-8*	Advanced Water and Wastewater Treatment: Implications and Prospects for the Construction Industry	Haugland, Lindsay Ann
94-9	A Comparative Analysis of Railway Project Financing: Case Studies of High-Speed Railway Projects in the U.S. and Japan	Mitani, Kuniaki
94-10	Automation of the Parking Industry: A Strategy and Managerial Overview	Abboud, Nicolas W.
94-11	The European Union's Single Market Initiative: A New Context for Construction	Brazier, Jonathan S.
94-12	Construction Financing in a Hyper-Inflationary Economic Environment: Case of Venezuela	Brief, Ionathan
94-13	Primary Consultant Options for Capital Project Planning: A Market Analysis and Selection Methodology	Davies, Thomas K.
94-14	Comparative Analysis of U.S. and EC Environmental Institutions and Policies to Proposed Lebanese Government	Fakhry, Walid K.
94-15	Public-Private Partnerships for the Reconstruction of Lebanon: An Application to Power Generation	Hamiyeh, Nagi A. Mikati, Rachid
94-16	A Comparative Study of BOT in Developing Asian Countries	Izuka, Hlroaki
94-17	Gaining Competitive Advantage Through Collaboration:Options for Minority Architecture and Engineering	Lewin, Denise
94-18	Re-engineering Construction Operations	MacLeod, Stefan Scott
94-19	Scope Management	Nayyar, Munir Khan
94-20	Application of Option Valuation Techniques in Valuing Petroleum Leases	Shikari, Sohel K.
94-21	Analysis of Energy Service Industry	Soma, Ichiro
94-22	Institutional Design for IVHS in Osaka: Applying the concept of ISTEA in Japan	Takahashi, Toru
94-23*	Task and Environmental Uncertainty and the Adoption of Technological Innovations by Home Builders	Toole, T. Michael

94-24	Diversification Strategies for Construction Companies	Tsai, Chih-Che
94-25	Comparative Overseas Strategies: Perspectives of the Japanese Engineering and Construction Industry	Washimi, Takashi
94-26	Contracting Methods and Risks in Federal Remediation Projects	Peter K. Sherrill
94-27	Marketing in the Construction Industry: An Analysis of Its Development, Current Status and Future Direction	James A. Maconochie
94-28	Energy-Related Technologies: Five Technologies for Lower Energy Demand and Decreased Air Emissions	Matthew W. Steele Kazushi Wakita
94-29	Advanced Water and Wastewater Treatment: Implications and Prospects for the Construction Industry	Lindsay A. Haugland Eric Martin
94-30	Hazardous Waste Site Remediation	Jennifer L. Griffith Yoshio Suto
94-31	A Comparison of Construction Automation in Major Constraints and Potential Techniques for Automation in the United States, Japan and Taiwan	Jen-Chi Hsiao
94-32	Privatization in Mexico: Its Role in the Economy and the Development of the Public Infrastructure	Jose Carlos Galindo Gutierrez
94-33	Design Rationale for Computer Supported Conflict Mitigation During the Design Construction Process of Large-Scale Civil Engineering Systems	Feniosky A. Pena-Mora
94-34*	Condition Data Reduction for Pavement Mangemenent	Ravi G. Mishalani Haris Kotopoulos
94-35*	Improved Methods for Classification of Pavement Distress Images	Kapotis Koutsopoulos Downey
94-36*	A Framework for Performance Based Design	Albano Connor Suh
94-37*	Modeling the Spatial Structure of Facility Condition	Mishalani, Koutsopoulos
94-38*	Mechanical Behavior of Butyl Adhesives	Rao Connor

PART III ACADEMIC ACTIVITIES

STUDENTS

SUBJECTS

THESES

The Center's academic mission is implemented through the direction and administration of the graduate degree programs in Construction Engineering and Management. These programs, which lead to Masters, Engineers, and Doctors degrees, help prepare students for a variety of career opportunities in the construction industry. CCRE graduates occupy management, technical and professional positions not only in construction firms but also in owner organizations, government agencies, engineering and design firms, and other companies that supply important materials products, and services to the industry. In addition an increasing number of Ph.D. candidates in the program are preparing for academic teaching and research careers.

The Program for Advanced Construction Technology has made substantial and far-reaching impacts on the academic programs in construction with respect to the size and character of student enrollment, the breadth and content of the curriculum, and the nature and quality of student theses and other publications. These impacts are discussed in the following sections and are illustrated in the various exhibits presented.

STUDENT ENROLLMENT

Table 1 presents some of the statistics on student enrollment since the establishment of CCRE in early 1982.

The impact of PACT, which was initiated in September 1986 with the Fellowship Program, is reflected in the statistics. Overall enrollment increased from approximately 34 students to a level of 50, and the number of Ph.D. candidates in the program increased more than threefold. The percentage of U.S. versus international students increased to the 60 percent range, and the number of MIT/CCRE students receiving direct financial support more than tripled from a pre-PACT average of 7 to a high of 26.

The substantial increase in the number of students directly supported by CCRE is, of course, a direct result of the Fellowship Program. Students receiving these Fellowships and their areas of study are listed in Exhibit I. Exhibit J contains summary information on their research areas.

Exhibit K is a listing of research theses prepared by CCRE students and PACT research assistants from 1982 to 1994 categorized by research area.

TABLE 1: STUDENT STATISTICS

Enrollment as of September	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994
Doctor	6	8	5	7	14	20	22	20	16	15	11	11	9
Master	28	26	23	29	32	29	28	27	38	36	38	48	33
Total	34	34	28	36	46	49	50	47	54	51	49	59	42
Students with Financial Aid													
Number	7	10	9	15	21	20	23	22	24	26	20	25	16
Percentage	20%	29%	32%	42%	46%	41%	46%	47%	44%	51%	42%	42%	38%
U.S. Students													
Number	16	15	12	17	21	31	33	27	32	29	26	26	22
Percentage	47%	44%	43%	47%	46%	63%	66%	58%	59%	57%	53%	44%	52%
Degrees Awarded													
Doctor	2	1	2	1	0	0	1	5	3	5	5	1	2
Engineer	0	1	2	0	1	1	1	0	0	1	0	0	0
Master	10	13	18	12	14	21	19	15	14	19	24	17	28
Total	12	15	22	13	15	22	21	20	17	25	29	18	30

Exhibit K

CENTER FOR CONSTRUCTION RESEARCH AND EDUCATION

THESIS TITLES 1982-1994

TECHNOLOGY

AUTOMATION & ROBOTICS

1987

LEVY, DAVID*

Studbot: A Construction Robot for the Automated Assembly of Steel-Stud Partition Walls
SMCE 9/87

SCHENA, BRUCE*

Design Methodology for LARGE Volume Robotic Manipulations: Theory and Application
SMCE 9/87

1980

ALONSO HOLTORF, VICTOR**

A Study of Automation Potential in Commercial Building Construction
SMCE 2/88

ZIEGLER, ANDREW*

The Design and Fabrication of an Automated Shear Stud Welding System
SMCE 6/88

1989

DEMSETZ, LAURA**

Task identification and Machine Design for Construction Automation
Ph.D. 5/89

HEATZIG, ERIC*

Design and Implementation of a High-Speed DSP Motion Controller
SMCE/89

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* Denotes PACT Research Assistant

** Denotes PACT Fellowship

1991

ALTOBELLI, FRANK ROBERT**

An Innovative Technology in Concrete Construction: Semi-Automated Rebar Tying
SMCE 2/91

EVERETT, JOHN G.**

Construction Automation: Basic Task Selection and Development of the CRANIUM
Ph.D. 5/91

1995

HSIAO, JEN-CHI

A Comparison of Construction Automation in Major Constraints and Potential Techniques for Automation in the U.S., Japan, and Taiwan
SMCE 12/95

ADVANCED MATERIALS

1986

AHDAB, MISBAH M.

Behavior of Fiber-Reinforced Mortar in Compression
SMCE 2/86

1987

SIT, EDWARD TAK-WAH

The Use of Visoelastic Dampers to Control Wind-Induced Vibrations in Tall Buildings
SMCE 6/87

TRIANTIFILLOU, THANASIS*

Failure Mode Maps and Minimum Weight Design For Structural Sandwich Beams with Rigid Foam Cores
SMCE 2/87

WU, MAO S*.

Continum Modeling of Sea Ice
SMCE 2/87

BRACH, ANN MARGARET**

The Potential for Advanced Ceramic Materials in Construction
SMCE 6/87

1988

NGUYEN, NHUY
Reinforced Concrete Corbel: A Case Study
SMCE 6/88

1989

GREEN, ERIC**
Behavior of High Strength Fiber Reinforced Concrete
SMCE 6/89

KUCIRKA, MARK*
Analysis and Design of Sandwich Panel Residential
Rod Systems
SMCE 6/89

TRIANTIFILLOU, THANASIS*
Multi-Axial Failure Criteria for Cellular Materials
Ph.D. 6/89

1990

LEUNG, CHRISTOPHER*
Micromechanical Modelling of Short-Fiber
Reinforced Ceramics
Ph.D. 5/90

TOOLE, T. MICHAEL**
Strategic Issues in Stresskin Foam Panels in
Residential Construction
SMCE 6/90

1991

PLEVRIS, NIKOLAOS T.*
Strengthening and/or Reinforcing Structures with
Fiber-Reinforced Plastic Composite Sheets
SMCE 2/91

TONYAN, TIMOTHY DONALD**
Mechanical Behavior of Cementitious Foams
Ph.D. 2/91

GANTES, CHARALAMBOS*
A Design Methodology for Deployable Structures
Ph.D. 5/91

HUANG, JON-SHIN B.*
Foam Core Materials for Structural Sandwich Panels
Ph.D. 5/91

1992

CHI, JEFFREY*
Micromechanical Modeling of Ductile-Fiber-Reinforced Ceramics
SMCE 2/92

RAO, C. LAKSHMANA *
Deformation and Failure of Adhesively Bonded Elastomeric Lap Joints
Ph.D. 2/92

1993

COMBIER, LAURENT A.
Diffusion of Innovation in the Construction Industry: High Strength Concretes
SMCE 2/93

PHELAN, RANDALL S. **
High Performance MAGLEV Guideway Design
SMCE 2/93

SHAHBAZKER, AMJAD
Shear Behavior of Fiber Reinforced High Strength Concrete Beams
SMCE 2/93

1994

RICHMAN, JUDAH LEE
Accelerated Methods of Residential Construction-Prefabrication Re-evaluated
SMCE 2/94

COMPUTERS & INFORMATION TECHNOLOGY

1982

CARTIN, BERNARDO
An Automated Successive Estimation Process
SMCE 9/82

1983

PATEL, DILLESH
Development of an Expert System for Finite Element Analysis
SMCE 5/83

1984

CALDERON-ZAMORANO, JORGE
Design of an Information Systems for Reduction of Claims in Construction
SMCE 6/84

CHEESMAN, MARIA ELENA
Linear Sheduling Using Experience Curves
SMCE 2/84

MORAD, AYMAN A.
Optimal Selection of Project Bid: Computer-Aided Approach
SMCE 9/84

RAOUL-DUVAL, DIDIER
Valuation Models for Risky Projects : A CAPM Approach
SMCE 2/84

1985

CHANG SING, PAMELA
Simulating the Architectural Practice - An Evaluation of the Applicability of an Existing User's Model
SMCE 6/85

NAVINCHANDRA, DUNDEE J.
Intelligent Use of Constraints for Activity Scheduling
SMCE 6/85

NAY III, LESTON BELA
An Expert Systems Framework for Analyzing Construction Project Risks
SMCE 2/85

1986

ALDANA, JUAN CARLOS
Knowledge-Based System for Construction Program Scheduling and Forecasting
SMCE 6/86

ARIAS TORO, MAURICIO
Knowledge-Based Planning Schedules for Public Works Projects
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DELATTE, NORBERT J.
Characterization of Dynamic Vehicle-Pavement Interaction
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Quantitative Learning and Qualitive Reasoning About Failure Mechanisms in Pavement
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LOVESKY, GARY A.
Development of a Knowledge-Based System For the Condition Evaluation of Lock Gates
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SEYMOUR, CPT. WILLIAM J., P.E.
Preliminary Development of a Bridge Management System with Rule Based Expert System Decision Support
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1987

BRISSON, FRANCOISE
Knowledge-Based Expert System for Planning and Monitoring Construction Projects
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CHUNG, SE-HACK
The Expert System for Resource Constrained Scheduling
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Expert-MCA: A Knowledge-Based Naturaly Language Interface to CAPCES Database
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IVAN JOHN N.
CAPES: A Cafeteria Architectural Planning Expert System
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MIA for Disaster Handling : A Case Study
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WHITEMAN, WAYNE E.
A Disturbing Scheduling Technique for Managing Renovation Work
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1988

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Expert-MCA, An Expert System for CAPCES Databases
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CHERNEFF, JONATHAN**
Automatic Generation of Construction Schedule from Architectural Drawings
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NAVINCHANDRA, DUNDEE J.
Exploring Innovative Designs by Relaxing Criteria and Reasoning form Precedent Knowledge
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1989

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Development of An Application for Generator For GRASS
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A Blackboard Architecture of Communication and Coordination in Design
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Discrete Event Simulation of Construction Process
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ASALVO: A Knowledge-Based Expert System
for The Seismic Safety
Assesment of Existing Structures
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Practical Issues in Message-Passage Style
CDM Scheduling
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Knowledge Processing for a Construction
Management Database
Ph.D. 2/89

1990

CHERNEFF, JONATHAN**
Knowledge-Based Interpretation of Architectural
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Ph.D. 9/90

EL-SHAFEI, NAYEL
Specification-Driven Design
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Contract Detention, Collision Forces and Friction
for Physically Based Virtual World Modelling
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1991

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Transaction and Version Management in
Object-Oriented Database Management Systems for
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Development of a Computer-Aided Engineering Tool
for Prefabricated Concrete Frames
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An Intelligent CAD System as a Constructability
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A Generic conceptual Design Framework:CONGEN & COSMOS
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Design Process Information and Goal Achievement
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1992

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An Axiomatic Approach toPerformance-Based Design
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Optimal Design of Fendering System for
Marine Pier
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Communication and Information in
the Building Delivery Process
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Knowledge Acquisition in Conceptual
Project Scheduling
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Multiobjective Structural Design for
Constructable Facilities
Ph.D 2/92

1993

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Quantity Surveys From Shared CAD Object Models:
A Development Strategy
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Quality Cost Models for Construction Firms: A Strategic
Information Systems Approach
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Design Rationale for Computer Supported Conflict Mitigation
During the Design-Construction Process of Large-Scale
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REMOTE SENSING & DIAGNOSTICS

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Use and Interpretation of High-Speed Sensors in the
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Detection of SUBSURFACE Fluids and its Application to
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Detection of Leakage form Large Storage Tanks
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Automation of the Visual Inspection of Constructed
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Digital Signature Analysis of Radar Reflections for the Assessment of Concrete Bridge Deck Deterioration
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Theory and Methods of Analyzing Infrastructure Inspection Output: Application to Highway Pavement Surface Condition Evaluation
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Using Infared Themography to Measure the the Maturity of Concrete
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Application of Statistical Pattern Recognition to the Identification of Pavement Distress
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Computer-Based Segmentation and Interpretation of Pavement Surface Distress Images
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Assessment of Radar Technology for Concrete Damage
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Scattering of Elastic Waves by Steel Reinforcement in Concrete
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Condition Assessment of Reinforced Concrete Structures Using Electromagnetic Waves
Ph. D. 2/90

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Infrastructure and Technological Change: Assessing the Economic Consequences of Heavier Axle Loads in the Railroad Industry
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Assessment of Radar Technology for Determining the Thickness of Pavement Layers
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Optimizing Sequential Decisions Under Measurement and Forecasting Uncertainly: Application to Infrastructure Inspection Maintenance, and Rehabilitation
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Modeling Infrastructure Performance and User Costs
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TADEU, ANTONIO JOSE BARRETO*
Modelling and Seismic Imaging of Buried Structures
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DECISION/RISK ANALYSIS

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AL-ZABEN, HANI IBRAHAM
Energy Use in Construction Materials for Building Floor System
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Impact of Risk Allocation on Engineering Design of Subway Tunnels
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The Simultaneous Prediction of Equilibrium on Large-Scale Networks: A Unified Consistent Methodology for Transportation Planning
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Simulation of Costs and Performance in Egyptian Inter City Transportation
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Allocation of Life-Cycle Highway Pavement Costs
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1983

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Stochastic and Economic Evaluation of Adaptability in Tunneling Design and Construction
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Decision Analysis Case Study Using Insurance/Self-Insurance Tools in Remedial Geotechnical Work
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Use of Multiple Objective Analysis Techniques in the Evaluation of Low Volume Rural Penetration Road Investments
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Lanslide Risk Along Lake Roosevelt
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Decision Support Framework in Adaptable Tunneling
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The Economic Value of Geological Exploration as a Risk Reduction Strategy in Underground Construction
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Integrating Material Scheduling Into Construction Unit Decisions
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An Analysis and Development of A Rationale for Establishing a Common Regional System or Issuing Permits for Oversize and Overweight Trucks Engaged in Interstate Travel in New England
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A Framework for Facility Modification
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Risk and Returns in Commercial Real Estate: An Exploration of Some Fundamental Relationships
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Guaranteed Maximum Price Construction Contracts and the Use of Monte Carlo Simulation for Cost Projects
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Project Cost Increased Due to Risk and Need for Work Premiums: An Empirical Study of Bidding in the Construction Industry
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Economic Feasibility Study of An Office Off-Peak Cooling System Using Phase Change Materials
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Land and Housing Needs in a Modern Urban Area
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"Up-Down" Construction: A Feasability Study of its Application in the U.S.
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Anticipating the Market for Technological Innovations in the Home Building Industry
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A Strategy for Technology Transfer with an Example Application of the Water Resources Industry
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Innovation in the U.S. Army Corps of Engineers:A Case Study of Fort Drum
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Contextual Knowledge and the Diffusion of Technology Construction
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Hazardous Waste Remediation and the U.S. Army Corps of Engineers: Facilitating Technological Innovation Through Construction Management
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Strategic Spill-Over Production, Virtual , and Incentives for Research and Development
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The Hazardous Waste Remediation Market: Innovative Technological Development and the Growing Involvement of the Construction Industry
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A Design Method for Cross-Disciplinary Coordination and Innovation
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Evaluation of Three Industrialized Construction Systems for Budget Hotel Construction
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Rapid Innovation and Integration of Components: Comparison of User and Manufacturer Innovations Through a Study of Residential Construction
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1993

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Episodic Patterns in the Introduction of New Technologies: AEC Firms in the US and Japan
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Task and Environmental Uncertainty and the Adoption of Technological Innovations by Home Builders
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PRODUCTIVITY/COMPETITIVENESS

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Project Control for Building Development: A Case Study of a Real Estate Developer
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The Effect of Cyclical Construction Demand on the Performance and Operation of Construction Firms
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Issues and Strategies for Improving Constructability
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Productivity in Construction: An Issue of Measurement and Analysis
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Construction Productivity: Recent Downturn and Alternative Improvement Methods
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Construction and Maintenance Concerns for High Speed Maglev Transportation Systems
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Strategic Flexibility, Real Options, and Product-Based Strategy
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The Role of R & D in Construction Firms
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Accelerated Methods of Residential Construction Pre-Fabrication Re-Evaluated
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MANAGEMENT

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Change Orders-Identifying Key Factors and Their Impact on Construction Projects
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Quantifying the Impact of Owner Actions on Construction Costs
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Changes in Railroad Organizations for Major Improvement Programs
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Computer Based Information Systems in Construction Management Usage and Resistance
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Strategic Planning in Several Small Construction Companies, 1970-1982
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Inventory Management Control System for Building Construction Tenant Work
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Problems of the Nuclear Power Industry: The Washington Public Power Supply System Case
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Critical Success Factors for Determining the Information Needs for a Company in the Construction Industry
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The Role of Organizational Strategy in Developing C.B.I.S. for Construction Firms
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The Effects of Liability and Litigation Exposure on Architecture and Engineering Firms
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Longitudinal Study of the Programs and the Organization of a Division of the Corps of Engineers
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CDM Use in Top 400 Construction Firms
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Directing Organizational Change in Public Works Organizations: A Contingency Approach to Monitoring Effectiveness
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High Differentiation and High Integration of Larger Projects: The Reasons for and Essence of Overall Project Management
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An Analysis of the Facility Preventive Maintenance Program at the U.S. Naval Academy
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Modeling Real Estate Development Firms: A Structured Framework for Analysis
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Quality Assurance in Facility Procurement
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Design-Build in the Public Sector: A Case Study for Three Correctional Facilities
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The Effects of Inadequate Component Inspection on Facility Repair Projects
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Networking and Connectivity in an Engineering Company
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Construction: The Foundation of National Defense
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Renovation of Occupied Office Buildings
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Analysis of Claims in U.S. Construction Projects
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Alternate Criteria for Selection of Public Construction Contractors
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A Review of the Major Issues Facing the United States Construction Industry - 1988
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Dispute Resolution in Construction
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Secure Tenure Production: A Land Dispute Resolution Process
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Infrastructure Management for Economically Depressed Communities: Problems and Strategies
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Small Family-Owned Construction Companies in Colombia: A Business Strategy
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Impact Analysis in Construction Management: A Case Study - Bogota IV Project. Empresa De Acueducto Y Alcantarillado De Bogota
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Case Study of the Impacts of Scheduling on Construction Costs
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Compatibility of Construction Contracting Methods with Projects and Owners
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Future Infrastructure Responsibilities: And Analysis of a Government Organization's Strategy
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Customer Service Quality in the Construction Industry
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Mega-Project Construction Management: The Corps of Engineers and Bechtel Group in Saudi Arabia
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Strategic Business Planning for the Minority Contractor
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Contract Administration of Department of Defense Environmental Restoration Contracts
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Core Competencies and Skills-Based Competition Among General Contractors
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Constructed Wetlands: A Growing Opportunity for the Construction Industry
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Turning "Green": Organizational Change in the Army Corps of Engineers, 1962-1991
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Strategic Information System for Standardized Building Business
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A Survey of the Environmental Construction Market
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The Department of Defense and the Construction Industry: Leadership Opportunities in Hazardous Waste Remediation Innovation
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Alternative Contracting Methods in the U.S. Army Corps of Engineers
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Solid Waste Management: Decision and Market Dilemmas
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Contracting Methods and Management Systems of Remedial Action Contracts Within the U.S. Navy's Installation Restoration Program
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A Study of Section 936 of the Federal Internal Revenue Code and Its Impact on Puerto Rico's Construction Industry
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The Developing Environment: An Investigation of Democratic Values, Environmental Trends, and Implications for Development (A Case Study of Columbia, Missouri).
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Deforestation: Policies Toward a More Sustainable Tropical Timber Industry
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The Public Sector Construction Industry: Analysis of Single-Project Partnering
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Automation of the Parking Industry: S trategic and Managerial Overview
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Advanced Water and Wastewater Treatment: Implications and Prospects for the Constructio Industry
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Gaining Competitive advantage through Collaboration: Options for Minority Architecture and Engineering Firms
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Re-engineering Construction Operations
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Scope Management
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Contracting Methods and Risks in Federal Remediation Projects
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Analysis of Energy Service Industry
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How Environmental Considerations Are Changing The Construction Industry: Five Technologies for Lower Energy Demand and Decreased Air Emissions
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Diversification Strategies for Construction Companies
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FINANCE

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International Construction Financing
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Optimal Investment Policies for Maintenance and Rehabilitation of Highway Pavements
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Application of the Option Valuation Model to Construction Projects
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Risk-Adjusted Modelling of Commercial Real Estate Investments
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Evaluation of Projects
SMCE & SM 2/84

LIBERMAN, DANIEL
Creative Financing in the Construction Industry with the Cooperation of the Public and Private Sectors
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Principles of Economic Efficiency Applied to Highway Infrastructure Problems
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1985

BERMUDEZ, JOSE MARCOS
Analysis and Qualification of Risk of Cost Overruns in Construction Projects
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Risk Assessment of Commercial Real Estate Investments
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1986

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Application of an Adjusted New Present Value Model to A Real Estate Development Project
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An Evaluation of Financial Packages: New Bosoporus Bridge Case
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Bridge Rehabilitation Versus Replacement Decision: A Survey of Financial Methods
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An Analysis of Real Estate Investment Trust as Applied to Real Estate Valuations
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A Financial Analysis of a Proposed New Panama Canal
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Islamic financial Principles and Their Application in Project Financing
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A Financial Evaluation of the Eurotunnel Project
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Foreign Exchange Exposure in International Construction
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A Financial Analysis of the Depression of the I-93 Central Artery in Boston, Massachusetts
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Guaranteed Maximum Price Construction Contracts and the Use of Monte Carlo Simulation for Cost Projections
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Application of Valuation by Components to Risk Measurement and Foreign Exchange Exposures in International Projects
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Eurotunnel: An Innovative Approach to Project Financing
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Financing Low Income Housing Projects Through Debt Conversion in Investment
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Financial Evaluation of Refinancing of the Eurotunnel Project
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Real Options and Afordable Alternatives: A Contingent Claims Approach to the Economics of Ownership
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Sustainable Development, Infrastructure and Environmental Investment and the Privatization Decision
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Feasibility of Privatization of Expressway in Japan
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Construction Financing in a Hyper-Inflationary Economic Environment: Case of Venezuela
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Public-Private Partnerships for the Reconstruction of Lebanon: An Application to Power Generation
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Financing Infrastructure Development in Mexico Through Public-Private Partnerships: The Huites Hydroelectric Dam
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Marketing in the Construction Industry: An Analysis of Its Development, Current Status and Future Direction
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A Comparative Analysis of Railway Project Financing: Case Studies
of High-Speed Railway Projects in the U.S. and Japan
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Application of Option Valuation Techniques in Valuing Petroleum
Leases
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MANPOWER

1983

ABOURACHED, CHARBEL
Project/Manpower Management System for A Large Engineering/Consulting Organization
SMCE 2/83

TAYLOR, EDWARD
Future Roles of the Geotechnical Engineer in the Building Sector of the Construction Industry
SMCE 2/83

1984

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Manpower Planning in Construction Engineering Companies
SMCE 2/84

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Undergraduate Civil Engineering Education: Current Approaches
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Education and Training of Construction Managers in Mexico
SMCE 6/84

1985

YEH, JACK Y.
Integrating Labor Management and Project Control Systems on Construction Sites
SMCE 6/85

1992

TOMLINSON-DYKENS, SUSAN ANN**
Executive Education Programs in the Construction Industry: An Analysis of Existing National Programs and Current Industry Participation
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GLOBALIZATION/INTERNATIONAL

1982

DAKROURI, AHMED HANI
Project Managers and the Egyptian Construction Environment
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1983

MURAD, RUWAYN
The Construction Materials Industries and the Construction Activity in Lebanon
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Feasability of Gypsum Quarrying and Gypsum-Based Construction Product Manufacturing in Egypt
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SELIM, TAREK
Development of Construction Industry in Egypt
CE 5/83

1985

YANAUCHI, MASANORI
International Marketing Screening Model for Japanese Contractors
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1986

CHO,KAB RAE
U.S. Construction Industry as a Potential Market for Korean International Construction Industry
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Robotics and High-Tech: An Advantage of Japanese Contractors
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Technology of Cement Production: Issues and Options for Developing Countries
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Evaluation of a National Training Program in the Mexican Construction Industry
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Potential of U.S. Construction Market for Japanese Construction Firms
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1987

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Construction Industry and its Role in Lebanese Economy
SMCE 2/87

CHIBA, TAKFUMI
U.S./Japan Trade in Construction
SMCE 2/87

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Productivity of the Construction Industry: The U.S. and Japanese Cases
ENG. 6/87

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Construction Industry in France
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1988

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Development in China: A Feasability Study for a Mixed-Use Real Estate Development Project in the People's Republic of China
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Financing the Reconstruction of Lebanon
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An Evaluation of a Contractor's Position in Project Financing: A Case Study of a Japanese Construction Firm in the U.S.
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1989

ISMAIL, AHMED
Framework and Database for Organizing External Information for Strategic Management in the Construction Industry: Application to the Egyptian Market
Ph.D. 6/89

1990

SELWAN, FADI
The Build-Operate Transfer Model for Construction Projects: Issues and Applications to Turkey and France
SMCE 6/90

SUGIMOTO, FUMIO
Globalization of International Engineering and Construction Firms for Building Their Competitiveness
Ph.D. 2/90

1991

FERNANDEZ MILITINO JAVIER, FRANCISCO
Strategies Available to Spanish Construction and Engineering Firms in Order to Compete in the New Emerging European Market
SMCE 2/91

HAFFAR, RAMZI MUKHTAR
Public/Private Partnerships and Their Role in Providing Needed Projects in Jordan
SMCE 2/91

MONTANA ROBAYO, FERNANDO AUGISTO
Innovation in Industrialized Construction Processes as a Source of Competitive Advantage with a Case Study of an Industrialized System in Colombia
SMCE 2/91

OYAMA, KOJI
A Comparative Study of the U.S. - Japan Construction Industry
SMCE 5/91

PUA, SECK-GUAN
Establishing Effective Joint Ventures Between American Hotel Companies and Asia Pacific Rim Corporations
SMCE 5/91

1992

ASAHARA, TATSUHIKO
Customer Service Quality Management in the Construction Industry: A Comparative Study of the U.S. and Japan
6/92

BAKER, BRIAN L.
The U.S. Army Corps of Engineers' Role in Reconstruction of Kuwait: A Case Study and its Implications for Future International Missions
SMCE 2/92

BOUSTANY, SAMI A.
Privatization and Its Role in the Reconstruction of Lebanon
SMCE 6/92

HATANO, KEN
Analysis of Information Flow of Facility Management in a Japanese General Contractor with Focus on HVAC Systems
SMCE 6/92

INAGAWA, HISASHI
Potential of Strategic Information Systems for Japanese Construction Firms
SMCE 6/92

MARDELLI, ADEL B.
Repair Versus Development in the Reconstruction of Lebanon: A Case Study of the Metropolitan Beirut Water Supply System
SMCE 6/92

PANDIS, HARALABOS N.
Financial, Organizational and Technology Strategies for Wastewater Treatment Projects in Small and Medium Size Coastal Municipalities in Greece
SMCE 2/92

STERENFELD, JACKS
Exploring the Municpal Solid Waste Recycling Option: The Case of Sao Paulo, Brazil
SMCE 2/92

1993

BENITEZ MALVIDO, PEDRO LUIS
An Evaluation of the North America Free Trade Agreement and Its Effect on the Mexican Construction Industry
SMCE 5/93

DOMINGUEZ HIGUERA, LUIS MIGUEL
The Spanish Construction Opportunities and Challenges Beyond 1992
SMCE 2/93

FREY WALTER C.
Water for Life: Fighting Water Pollution in Eastern Europe
SMCE 2/93

HONG, JONGMIN
Competitive Strategies for Korean Construction Firms for Changing Circumstances
SMCE 2/93

1994

BRAZIER, JONATHAN S.
The European Union's Single Market Initiative: A New Context for Construction
SMCE 5/94

FAKHRY, WALID K.
Comparative Analysis of U.S. and EC Environmental Institutions and Policies to Proposed Lebanese Government
SMCE 5/94

GALINDO GUTIERREZ, JOSE CARLOS
Privatization in Mexico: Its Role in the Economy and the Develoment of the Public Infrastructure
SMCE 5/94

GOMEZ BARQUIN, GONZALO
Strategies of the Major Spanish Construction Companies for Improving Their Domestic and International Competitiveness
SMCE 2/94

TAKAHASHI, TORU

Institutional Design for IVHS in Osaka: Applying the Concept of ISTEA in Japan
SMCE 5.94

TORNIKIDIS, NIKOS

Investing in the Czech Republic
SMCE 2/94

WASHIMI, TAKASHI

Comparative Overseas Strategies: Perspectives of the Japanese Engineering and Construction Industry
SMCE 5/94

YAZBEK, KARIM

Public-Private Large-Scale Downtown Redevelopment in the Middle East
SMCE 5/94

CONSTRUCTION CURRICULUM

Exhibit L lists a number of graduate subjects which are relevant to construction engineering and management students. The PACT contribution to this curriculum included the development of five completely new subjects and major content revisions for an additional eight subjects.

EXHIBIT I: PACT FELLOWSHIP STUDENTS

Name		Area of Study and Research
Albano, Leonard D.	(Ph.D 2/92)	Performance-Based Design
Alonso-Holtorf, Victor A.	(SMCE 2/88)	Automation Potential in Commercial Building Construction
Altobelli, Frank R.	(SMCE 2/91) (Expected Ph.D. 5/95)	Construction Off-Site Automation
Brach, Ann M.	(SMCE 6/88) (Ph.D. 5/91)	Diffusion of Technology in the Construction Industry
Cherneff, Jonathan M.	(SMCE 6/88) (Ph.D. 9/90)	Knowledge-Based Interpretation of Architectural Drawings
Demsetz, Laura	(Ph.D. 2/89)	Construction Automation
Ernst, Michael J.	(Ph.D)	Hazardous Waste Monitoring Probe
Everett, John G.	(Ph.D. 5/91)	Construction Automation
Fischer, Jacqueline	(SMCE 2/90)	Intelligent CAD System for Constructability
Ford, David	(Ph.D. 5/95)	Information Technology and The Building Process
Geltner, David M.	(Ph.D. 6/89)	Risk Evaluation for Construction Projects
Green, Eric E.	(SMCE 6/89)	Behavior of High Strength Fiber Reinforced Concrete
Hoffman, Andrew	(SMCE 9/91) (Ph.D. 2/95)	Innovation and Technology For Environmental Protection
Miller, John B.	(Excepted Ph.D. 2/96)	Infrastructure Development
Pflueger, John C.	(Ph.D. 5/91)	Design Methods for Cross Disciplinary Coordination and Innovation
Phelan, R. Scott	(SMCE 6/90) (Ph.D. 2/93)	High Performance MAGLEV Guideway Design
Sanchez, Ronald	(Ph.D. 9/91)	Strategic Flexibility, Real Options, and Product-Based Strategy

PACT FELLOWSHIP STUDENTS (CONTINUED)

Slaughter, E. Sarah	(SMTP 6/87) (Ph.D. 9/91)	Diffusion of Technology in the Residential Construction Industry
Taylor, Henry F.	(SMCE 2/92) (Ph.D. In progress)	Environmental Technology/Solid Waste Management
Tonyan, Timothy D.	(SMCE 2/88) (Ph.D. 2/90)	Mechanical Behavior of Cementitious Foams
Toole, T. Michael	(SMCE 6/90) (Ph.D. 5/94)	Technological Innovation in Construction

EXHIBIT J
SUMMARY INFORMATION ON PACT FELLOWSHIP STUDENTS

(1) ALBANO, LEONARD D.

Ph.D. (2/92)
AN AXIMOTIC APPROACH TO PERFORMANCE-BASED DESIGN

Citing product quality as a mechanism for advancing the competitive advantage of the U.S. construction industry, this thesis outlines and demonstrates a methodology for performance-based design of constructed facilities. The concept of performance-based design is offered as a strategy for facility development; a rational basis for satisfying owners' requirements in various areas of project performance, such as function, durability, ease of construction, and ease of maintenance. The proposed methodology is a systems-based approach to design where the principles of axiomatic design as advanced by Dr. Nam P. Suh provide a mathematical framework for making the implications of various design alternatives explicit and for reasoning about the merit of design decisions.

Specifically, the Independence Axiom is used to ensure feasible solution concepts that are controllable, and the information Axiom is used to quantify "how well a proposed design satisfies the governing requirements." The Information Axiom has been extended to include the notion of an Interface Index as a quantitative design aid for reasoning about the complexity associated with system integration. The proposed index is an information-based metric derived from graph theory, and it is similar to the family of complexity metrics that have been developed for evaluating the modularity of software systems. The validity of the proposed design methodology, including the Interface Index, is demonstrated through application to a case study.

(2) ALONSO-HOLTORF, VICTOR A.

SMCE 2/88
A STUDY OF AUTOMATION POTENTIAL IN COMMERCIAL BUILDING CONSTRUCTION

The purpose of this thesis is to provide guidelines for the direction of automation applications and research in the building construction industry. The research analyzes the commercial building industry and commercial building construction processes, in order to determine which types of construction processes are best suited to automation from both economic and technological perspectives.

The first part of the research determines cost distributions among different building types and for different building processes. Ultimately, the justification for the introduction of advanced technologies in the industry is cost reduction. Knowledge of cost distributions reveals where the greatest potential impact on the industry can be made with the introduction of automation. Cost distributions are determined by construction process and building type, and then each total cost is broken down into labor and materials components. In addition, the financial effects of each process are analyzed by studying their effects on total project completion time.

The second part of the research analyzes construction processes for susceptibility to automation. Considering the technology available in a five to ten year horizon, processes are considered for physical susceptibility to automation. Additionally, individual economic analyses are undertaken for each process. Finally, correlations between cost distributions and total automation susceptibility are developed to determine which construction processes should be further studied.

The final part of the research includes a detailed analysis of the items revealed in the second part. Micro and macro economics of processes and sub-processes are studies, as well as the appropriate trade structures and organization behavior. In addition,

transitional implications for each process are discussed. This part serves to solidify the conclusions from the second part, and to rank specific construction processes in an order which shows which processes deserve the most attention for automation efforts to best improve the industry.

(3) ALTOBELLI, FRANK R.

SMCE 2/91
AN INNOVATIVE TECHNOLOGY IN CONCRETE CONSTRUCTION: SEMI-AUTOMATED REBAR TYING

The technologies of concrete construction have undergone gradual, evolutionary changes since concrete became a popular material for construction. Furthermore, these technological developments can be characterized as an active, industry-wide progression from fully manual operations to fully automated operations. Although some operations are still performed manually, most have undergone some degree of mechanization, and some have progressed to the automation stage.

This thesis first looks at the motivation for the automation of rebar tying operations, from potential cost savings to improved quality and worker satisfaction. It then presents a snapshot of the current state of the art in concrete technology, as well as illustrating the major steps that individual technologies have taken on their evolution to the status quo. The thesis continues with a chapter covering the analysis of the task of rebar tying, with examples of other attempts to automate the task, and which outlines the functional requirements for a semi-automated rebar tying machine. Finally, a detailed design for a rebar tying mechanisms which satisfies the stated requirements is presented.

Ph.D. (Expected 5/95)
AUTOMATION IN OFF-SITE PRODUCTION OF HOUSING

This thesis research in investigating the optimal level of automation in off-site production of housing. Since it appears that value added is shifting to off-site production in the homebuilding industry, and since homebuilding is such a large industry, it is important to produce the products in the most efficient manner.

There is little or no theory on when to automate processes in homebuilding. While there is some theory on benefits of automation in general, little if any work has been done, that considers the unique conditions found in the homebuilding industry.

In addition to filling a gap in our understanding of homebuilding processes, the theory developed in this research can be generalized to form a broad theory of the application of automation to off-site production of modules for commercial construction, for production of components, and for other non-construction related processes.

In order to develop such a theory, automation "levels" must be defined in some non-ambiguous way. The factors that affect the optimal level of automation must be defined, and the relationship between these factors and the objective to be optimized (which also needs to be defined) must be determined with some mathematical formulae. Once the problem is set up in this manner, a solution utilizing know, accepted itemization techniques must be computed, including the boundary conditions under which the solution is valid.

The hypothesis being tested is that for off site production of housing, a highly automated production system linked with the information systems throughout the firm will provide the optimal configuration of production technology.

(4) BRACH, ANN MARGARET

SMCE 6/87
THE POTENTIAL FOR ADVANCED CERAMIC MATERIALS IN CONSTRUCTION

In the past several years advances in materials science and engineering have produced exotic, high-performance ceramics that have been applied in such diverse fields as electronics, machine tools, wear components, coatings, armor, magnets, and replacements for bone and teeth. These wide-ranging and growing applications result from the very desirable properties of advanced ceramics, including high (compressive) strength, resistance to wear and corrosion, tolerance of temperature extremes, and ability to exhibit different electrical, magnetic, mechanical, and optical properties. To date, however, very little effort has gone into investigating the possibilities of these very interesting and versatile materials for construction. Although the initial costs of advanced ceramics are higher than those of conventional construction materials, these costs may be justified by the superior performance and improvements of current construction practices that advanced ceramics may promote, the life-cycle benefits of improved facility performance (which may more than offset initially higher costs), and the need for such materials in unique, demanding, and very specialized facilities and applications.

The objective of this thesis is to identify and analyze the potential applications of advanced ceramics in construction. The research includes a survey of the status and direction of research and developments in advanced ceramics and ceramic composites; an analysis of the role of materials in construction in terms of materials' intensity of use; the identification of facilities, applications, and processes in construction where ceramics would be good candidates for introduction; analysis of the potential impacts of ceramics on facility performance and life-cycle costs and benefits; and conclusions as to the roles that ceramics might be expected to play in construction, their technical and economic advantages and disadvantages, new markets and possibilities posed by the unique characteristics of ceramics (whether existing or promised), and recommendations of areas for further investigation.

Ph.D. 5/91
CONTEXTUAL KNOWLEDGE AND THE DIFFUSION OF TECHNOLOGY IN CONSTRUCTION

The U.S. construction industry as a whole is not commonly viewed as a very technologically innovative industry. Yet a wide range of technologies is required for this industry to carry out its function, often to solve challenging problems in unique projects (harsh environments, etc.) Despite the importance of technology, construction does not engage in firm-sponsored R&D nor do many companies actively pursue new technologies for purchase or hire persons with advanced degrees in technological and scientific specialties. Nevertheless, construction firms do manage to procure innovative technologies when they are required for projects.

The central argument of this thesis is that the behavior of the construction industry in matters related to technology - learning about, acquiring and developing technology - is a consequence of the strong role of "contextual knowledge" in the industry. Contextual knowledge is knowledge linked to the context in which it is gained rather than known formally, abstracted from its context. Dependence on knowledge which remains closely linked with the context in which it is gained results in patterns of behavior which will differ from industries and activities which draw from formal or context-independent knowledge.

In this research a model of contextual knowledge is developed and its effect on construction's technology-related behavior is explored using a case study method. It is found that technology-related behaviors are largely dependent on the context (the construction project) in which the technology is or will be used. This pattern is most applicable in the development of process technology or construction technique. It is also

most accurately descriptive of the general contractor although such context-oriented behavior is also found in other participants such as the designer or the speciality contractor.

(5) CHERNEFF, JONATHAN M.

SMCE 6/88
AUTOMATIC GENERATION OF CONSTRUCTION SCHEDULES FROM ARCHITECTURAL DRAWINGS

Generating and maintaining schedules from architectural drawings is vital to both construction and design professionals. Automating the task requires combining a CAD system with knowledge based programming and database techniques. A prototype system, called BUILDER, is presented for the domain of routine interior office construction. The principal features of the BUILDER system are its knowledge representation scheme and its planning paradigm.

A knowledge representation scheme is demonstrated that enables the interplay of the drawing and the construction knowledge base. The features of the drawing are extracted and represented in a semantic network of frames. A forward chaining rule based expert system reasons about the semantic network of frames to produce a project network. The project network is represented in an object oriented style that can readily admit functional extension.

A knowledge intensive planning paradigm is found to be appropriate both in principle and because of the routine nature of the domain. A scheme that expands the Work Breakdown Structure prior to assigning precedences combined with conservative hierarchical planning is best suited to the domain.

Ph.D. 9/90
KNOWLEDGE-BASED INTERPRETATION OF ARCHITECTURAL DRAWINGS

Architectural schematic drawings have been used to communicate building designs for centuries. The symbolic language used in these drawings efficiently represents much of the intricacy of the building process (e.g., implied business relationships, common building practice, and properties of construction materials). The drawing language is an accepted standard representation for building design, something that modern data languages have failed to achieve. In fact, the lack of an accepted standard electronic representation has hampered efforts at computer integration and perhaps worsened industry fragmentation. In general, drawings must be interpreted, by a professional, and then re-entered in order to transfer them from one CAD system em to another.

This work develops a method for machine interpretation of architectural (or other) schematic drawings. The central problem is to build an efficient drawing parser (i.e., a program that identifies the semantic entities, characteristics, and relationships that are represented in the drawing). The parser is built from specifications of the drawing grammar and an underlying spatial model. The grammar describes what to look for, and the spatial model enables the parser to find it quickly. Coupled with existing optical recognition technology, this technique enables the use of drawings directly as: (I) a database to drive various AEC applications, (2) a communication protocol to integrate CAD systems, and (3) a traditional user interface.

(6) DEMSETZ, LAURA

Ph.D. 2/89
TASK IDENTIFICATION AND MACHINE DESIGN FOR CONSTRUCTION AUTOMATION

The last decade has seen increased interest in the automation of construction processes. Work in this area has proceed din two directions: the development of automated an robotic equipment, and the identification of construction tasks that are good candidates for automation. Especially in the area of task identification, there has been a failure to consider automation in a broad sense -- not as just the replacement of a worker by a robot, but rather as the augmentation of skilled human labor with sophisticated tools. This thesis examines a broader view of automation with respect to both task identification and machine design.

Previous task identification studies have addressed total automation using robotic manipulators. Approaches to automation in manufacturing and the success of partially automated heavy construction equipment indicate that this focus is too narrow. To avoid a priori assumptions regarding the extent of automation and the configuration of automated equipment, a two step procedure for task identification is proposed here. The first step, *preliminary selection,* is based solely on the potential for the anticipated benefits of automation: reduced labor requirements, increased speed of construction, increased safety, and improved quality. Sources of benefit data are evaluated, and recommendations are made regarding their use in preliminary selection. In the second step, *conceptual design,* an interdisciplinary team examines the various ways in which each of the previously selected tasks could be divided between man and machine. Their efforts result in conceptual designs for several machines, each representing a different degree of automation. A framework helpful in guiding the design team is developed, and recommendations for the team's composition are made.

Most of the automated machines developed to date for construction tasks handle the placing, spreading, or finishing of bulk material; none address both the positioning and fastening of discrete parts. The automation of interior partition wall installation is explored, and the division of labor framework is used in assessing the proposed designs. The design and fabrication of TRACKBOT, a machine to install the horizontal members of partition wall framework, provides an example of the automation of both the positioning and fastening of a discrete construction component.

(7) ERNST, MICHAEL J.

Ph.D. 8/12/94
MODELING MULTICOMPONENT VACUUM FLOW, TRANSPORT, AND OUTGASSING IN A MEMBRANE-INLET VAPOR SAMPLING PROBE

The measurement of subsurface contamination by Volatile Organic Chemicals (VOCs) is an important methodological problem as these contaminants are ubiquitous in the industrialized world. There is a great need for fast, reliable, and inexpensive means for the determination of the nature and extent of subsurface VO contamination. A prototype membrane-inlet vapor sampling probe for monitoring subsurface concentrations of VOCs in situ has been developed and tested. In this work, a detailed mathematical model of the probe describing the important vapor transport issues related to its operation has been constructed and tested against the prototype. The model includes conductance expressions for the entire vacuum regime from visous to molecular flow, a time and pressure dependent outgassing formulation, provisions for a membrane-inlet, and a complete description of the advective and diffusive transport of the sample vapor. The model is composed of a set of approximations in an iterative solution scheme. Experiment comparing model simulations with results from the prototype system have shown the model to be useful both for understanding how the system works and for evaluating alternative system designs. The process of modeling the vapor sampling

probe has shown existing theories of multicomponent transitional vacuum flow and vacuum outgassing to be insufficient, and has pointed toward new hypotheses concerning these phenomena.

(8) EVERETT, JOHN G.

Ph.D. 5/91
CONSTRUCTION AUTOMATION: BASIC TASK SELECTION AND DEVELOPMENT OF THE CRANIUM

This thesis reviews issues facing the construction industry and some of the strategies for addressing them. The thesis focuses on the development of automation technology and its potential for solving problems of productivity, safety, quality, and skilled labor shortages.

The most important step in developing automation technology is selecting appropriate tasks to automate. The new technology must be compatible with design, management capabilities, labor practices, and other field operations. The thesis introduces a taxonomy of the construction industry, in which the industry is broken into several levels of increasing detail. The thesis proposes that automation should be introduced at the Basic Task level. The thesis defines a set of eleven Basic Tasks from which all construction field work is composed. The Basic Tasks are prioritized for suitability for automation based on productivity, technology, safety, quality, and labor acceptance.

As an example of technology to improve the Basic Task Position, or heavy lifting, the CRANIUM crane mounted video system is developed. The CRANIUM extends the sensory capacity of the crane operator by allowing him to see the crane's load at all times and/or have visual contact with the craftsmen receiving the load. A full scale, fully operational prototype has been designed, fabricated, and field tested. Productivity improvements in excess of 20 percent are reported for some applications. The CRANIUM also improves safety and has been well received by labor and management.

(9) FISCHER, JACQUELINE

SMCE 2/90
AN INTELLIGENT CAD SYSTEM AS A CONSTRUCTABILITY ADVISOR

Most commercial computer-aided design systems have impressive graphic capabilities. However, beyond facilitating the production of quality drawings, they provide limited assistance to the actual design process. In order to provide this assistance, it is necessary for these systems to understand an ill-structured problem and formulate and evaluate possible solutions. Knowledge-based systems offers a programming methodology which can address these issues. This thesis focuses on the integration of these two technologies to produce an intelligent CAD system. The result of this integration is a system which can reason about the meaning of a design during the development of its graphical representation.

Constructability is an important characteristic of a building design. Oftentimes designers are unaware of the construction requirements for their design and opportunities for substantial time and cost savings in the construction phase of a project are overlooked during the design process. Unfortunately, it is during the design process that constructability problems and opportunities must be identified so that changes to solve these problems or to take advantage of these opportunities can be implemented. Once the design has been completed, many of the important decisions have been locked in and the chances of making any of these changes are diminished. This thesis examined the use of the intelligent CAD system to address this problem of constructability of design. An application has been developed for the constructability of cast-in-place concrete floor structural systems.

(10) FORD, DAVID N.

Ph.D. (5/95)
FLOW MODEL OF THE BUILDING DEVELOPMENT PROCESS

This research will deal with Object oriented Information Flow Model of the Building Development Process.

The Problem: The participants in the building development process utilize a bewildering number and variety of automated models to predict the impacts of their decisions and actions. No superstructure, model, or metasystem exists which can relate these analogs to each other and thereby integrate the project team, its actions, and its products. Without a unifying information storage and flow model the participants, products, and processes of building development cannot be simulated effectively. An information structure which is based upon a functional data flow model of building development and supports the simulation of all portions of the process is required to effectively coordinate the building development process.

The Hypothesis: An object oriented information storage and flow model can effectively simulate the building development process which consists of (I) Identifying information needs and flows required by the Building Development Process; (2) Developing a macroscopic functional Information Flow Model of the Building Development Process; (3) Developing an Object Oriented Information Storage Structure of the Information Flow Model of the Building Development Process (identifying the classes required, their hierarchical relationships, and the data and behavior required by each); and (4) Verifying the hypothesis by implementing a portion of the Information Flow Model in an existing object oriented environment.

(11) GELTNER, DAVID M.

Ph.D. 6/89
RISK AND RETURNS IN COMMERCIAL REAL ESTATE: AN EXPLORATION OF SOME FUNDAMENTAL RELATIONSHIPS

This thesis applies some basic tools from modern financial economic theory to gain some insight into the nature of commercial real estate valuation, return risk, and risk premia, relevant for the analysis and evaluation of construction projects in the private sector. The basic motivation for the thesis is the fact that, while risk in the returns to such projects is potentially quite important in their evaluation, it is difficult to study such risk because regular and frequent time series of returns to real properties cannot be observed, due to infrequent trading of such assets.

The thesis is divided into two parts. Part I develops a multi-period cash flow based valuation model, explicitly incorporating the use of long-term leases as is common in much commercial real estate. This model is then used to derive insights regarding the nature of the return risk, based upon the nature of the observable cash flow or rental market risk. The effect of lease term on return risk, and the accuracy of the sidely employed "simple cap rate valuation" method, are explored using this model, as well as the question of to what extent use of long-term leases may make some commercial real estate more "like a bond" than "like a stock."

Part II focuses on the use of appraisal based returns time series in the study of the nature of real estate return risk. Behavioral models of the appraisal process are developed which provide insight regarding the extent to which such time series may be "smoothed," that is, display less risk than is present in the true (unobservable) market value based returns. An empirical based approach to approximately correct for such smoothing is presented, and applied to a small sample using some widely cited indices of aggregate commercial real

estate values. This analysis indicates considerable smoothing, and also reveals that systematic risk defined with respect to national consumption (as suggested by the Consumption based Capital Asset Pricing Model) is much greater than systematic risk defined with respect to the stock market (as is usually done in applications of the CAPM to financial securities).

(12) GREEN, ERIC. C.

SMCE 6/89
BEHAVIOR OF HIGH STRENGTH FIBER REINFORCED CONCRETE

Concerns about brittle failure behavior and quality control of high strength concrete with compressive strengths greater than 6,00 psi, as well as the durability problems associated with cracking have prompted interest in techniques to improve ductility in high strength concrete. Fiber reinforcement in ordinary concrete and mortar has shown the ability to greatly increase toughness, ductility and durability. It may also improve flaw tolerance, reduce steel reinforcement requirements and increase constructability.

Synthetic ultra high strength polyethylene fibers are introduced into a high strength concrete and mortar matrix with a 28 day compressive strength of approximately 13,500 psi. Low fiber volume fractions of less than 1.0% are used. These fibers are also introduced into a medium and low strength concrete matrix, as well as a low strength mortar matrix. Compressive, flexural and direct tension test are performed on the resulting fiber reinforced concrete and mortar composites. Parameters measured include compressive strength, modulus of elasticity, failure strain, direct tensile strength, fracture energy, modulus of rupture and ACI toughness indices.

It is found that frictional bond strength is improved with decreasing w/c ratio. Thus, the fracture energy, G_c, increases with the matrix compressive strength. However, flexural ductility is decreased in cement based composites with higher strength matrices. This is due to a reduced ability to exhibit multiple cracking caused by high tensile strengths. This lack of ductility is demonstrated by low f_F/f_T ratios in high strength composites.

Fiber addition is shown to decrease modulus of elasticity, compressive strength, flexural strength and tensile strength. This is attributed to poor compaction of fiber reinforced composites caused by reduced workability. Production considerations are found to be as important as performance considerations in designing fiber reinforced high strength cement based composites.

(13) HOFFMAN, ANDREW J.

SMCE 9/91
THE HAZARDOUS WASTE REMEDIATION MARKET: INNOVATIVE TECHNOLOGICAL DEVELOPMENT AND THE GROWING INVOLVEMENT OF THE CONSTRUCTION INDUSTRY

The cleanup of hazardous waste disposal sites is a pressing national crisis due to the slow implementation of the cleanup of hazardous waste disposal sites under the ten year old Superfund program. However, implementation of the Superfund represents a growing market of enormous proportions for engineering and consulting firms through the emergence of new markets with DOE, DOD and others. Actual remediation construction work is only now beginning to materialize on a large scale, thus attracting a new player to the market: the construction industry. The first part of this thesis analyzes the role that construction firms will play in the hazardous was remediation market. They offer construction management skills that are far more experienced than what is presently available through traditional environmental contractors and consultants . As they assimilate into the market, they can be expected to create a more competitive environment for established environmental firms but, will also be required to alter their

own organizations in order to continue to compete. As the market becomes more competitive, remediation technologies that offer economic savings to the client will find an increasing market share. Bioremediation and in-situ verification offer great potential as economical and technically effective technologies for future remediation projects.

The second part of this thesis analyzes the obstacles and incentives to innovation in hazardous waste remediation technologies today. The need exists at this time for new technologies that are quicker, less costly, and provide more permanent destruction of toxics than are presently available. However, lack of pollution insurance,lack of available financing, and a cumbersome regulatory process increases the financial risks to the technology developer and ,thus,, tends to stifle innovation. Technology innovators are facing an uncertain regulatory and financial future as they bring their systems to the market. The EPA programs designed to ease these obstacles such as SITE, ATTIC and the new Indemnification Program are in place but are not producing effective results.

Existing remediation technologies are not as technically advanced or economically efficient as the market requires. Furthermore, new and innovative technologies are not entering the market as rapidly as is needed. when rating the criteria that make their technologies attractive to potential clients, vendors listed the applicability to certain wastes and capability of meeting EPA standards as the most important. This speed and low cost were not highly considered. In other words, they were more concerned with satisfying regulatory demands than market demands. Although this is, in part, due to the infancy of the market,it also underscore the dominating influence that the government has on the market and the extent of research.

In order for the EPA to promote technological development, it need not spend more money promoting research. It must strive to withdraw its regulatory influence on the technical aspects of the cleanup process and allow market forces to drive innovation. The EPA should take steps to eliminate the barriers between the technology vendor and the client, an d therefore,the economic profits.

To do this,the EPA should set firm and reasonable standards to which sites must e cleaned up. Then, it should streamline the remediation process so as to allow the responsible parties the latitude to choose whichever technology they feel will best allow them to achieve that standard. It should develop an efficient process for determining who the responsible parties are. And finally, it should develop an effective technology transfer program to accelerate the spread of information about the variety of remediation technologies that are now available as well as those that will become available in the future. In essence, the answer to promoting technological development is less,not more government intervention.

Ph.D. 2/95
THE ENVIRONMENTAL TRANSFORMATION OF AMERICAN INDUSTRY: AN INSTITUTIONAL ACCOUNT OF ORGANIZATIONAL EVOLUTION IN THE CHEMICAL AND PETROLEUM INDUSTRIES (1960-1993).

How have the structure and strategy of the American industrial enterprise evolved in response to environmentalism, and what are the dynamics by which this transformation has taken place? To answer these questions, this dissertation draws upon the theoretical field of organizational behavior and in particular, institutional theory. In explaining the emergence of corporate environmental management strategies, I find that what we have been witnessing over the past three decades has been the co-evolution of institutions outside the firm and the structures and strategies inside the firm. Both have been continually evolving as new events or crises call attention to the need for new forms of broadly accepted legitimate behavior. The status of corporate environmental management is explained as the historical product of this external examination, the result of what is described as a negotiation among the internal members of the firm and external

members of the institutional field: primarily the government, other firms sharing similar technological and political constraints, and external environmental interests.

Using a content analysis of two trade journals and a statistical review of federal case law, both studies being longitudinal from 1960 - 1993, this dissertation links the evolution of corporate attention and strategy, not simply with shifts in environmental costs, but rather with shifts in the makeup and power balances in the institutional field. Observed to be in an interactive relationship, the institutional field, corporate attention and corporate strategy were found to have evolved through a concurrent four stage evolution, with transitions in 1970, 1981-1983 and 1988-1990. To further build this analysis, case studies of the Amoco Corporation and the environmental investor group, the Council of Environmentally Responsible Economies (CERES) provide additional insights into the institutional model. These results have practical implications for the business manager, policy analyst and environmental activist and theoretical implications for the organizational theorist.

(14) MILLER, JOHN B.

Ph.D. (Expected 2/96)
INFRASTRUCTURE AND ECONOMIC DEVELOPMENT

The overall objective of this doctoral research s to propose different, effective means of aligning infrastructure delivery processes with improvements in economic activity in the United States. Infrastructure replacement, repair, and expansion have been detrimentally affected by the ascendancy of process over substance. As legislative and regulatory bodies "process" competing interests and claims over such questions as "who are the beneficiaries of particular projects" or "how should (insufficient) funds be allocated across desirable projects", the substantive goal -- a coordinated public/private strategy for delivering economical, efficient infrastructure -- languishes.

The current process fails to address basic questions. What infrastructure is needed to support our evolving economy? Which need should, or must, be met by government, by industry, or by a combination of the two? How might legislative/regulatory processes be structured to align our changing economy with the effective and efficient delivery of infrastructure development?

The research involves a close examination of old and new infrastructure delivery methods to suggest a path to consensus on these questions and a different, more effective approach for legislators and private entities to follow. As a direct outgrowth of the research several workable legislative and regulatory models will be developed to permit legislators and regulators to align common interests in infrastructure and economic development. These models will recommend strategic procurement techniques, such as best value and best practices, and propose multiple approaches for public, private, and public/private financing for needed infrastructure development.

(15) PFLUEGER, JOHN C.

Ph.D. 5/91
A DESIGN METHOD FOR CROSS-DISCIPLINARY COORDINATION AND INNOVATION

The traditional design process has proven to be effective in the past. Now, however, market forces represented in the form of stiff international competition have forced firms to search for ways to streamline this process and develop designs that can be brought to market as quickly as possible. Making major improvements in product quality and reducing the total production cycle time may require a move to a more structured design process or to more efficient design activities.

This thesis looks at techniques and mechanisms for improving the front-end of the design process for complex projects with a weak or no central authority structure. These efforts usually require the simultaneous design of many sub-systems, and their integration into one final product. The focus of this work is not on the individual designer, but on the way in which designers work together. The front-end of the design process includes defining the design problem, as well as developing and evaluating conceptual designs in a deliberate search for innovative solutions.

The procedure for developing the new design aids follows the same line as the development of a new product. Important tasks include defining the problem of improving design processes, suggesting possible solutions, and evaluating and reworking the same. The final product is intended to improve the representation of the design problem, improve the evaluation process for multi-disciplinary design concepts, make the design process more robust to changing conditions, improve communication among designers, and deliberately create situations where cross-disciplinary innovation is possible. Because of its lack of dependence on an existing central authority structure, the method presented in this work has the potential to be relatively structure free.

(16) PHELAN, RANDALL SCOTT

SMCE 6/90
CONSTRUCTION AND MAINTENANCE CONCERNS FOR HIGH SPEED MAGLEV TRANSPORTATION SYSTEMS

Though the demand for transportation services continues to increase beyond mere population growth, physical expansion options for existing facilities is limited. In addition, though efforts are being made to increase the capacity of current infrastructure systems through automated operational techniques, it is doubtful operation automation alone will be sufficient to meet future transportation demands. Additional transportation infrastructure construction is likely to be required. Increasingly, high speed ground transportation, HSGT, technologies in general, and high speed magnetically levitated, MAGLEV, systems in particular, are being viewed by transportation planners and officials as potential future transportation modes.

No true HSGT system currently is in operation in the United States. A number of recent U.S. federal and state government assisted studies have reviewed the feasibility of GSGT systems for markets in the U.S. with favorable results. However, though current interest in GSGT technology appears high, an appropriate level of concern directed towards construction and maintenance issues involved with such technologically complex systems has not been reflected.

This thesis investigates construction and maintenance concerns for high speed MAGLEV transportation systems. An overview of both MAGLEV and high speed rail technologies is provided and comparative systems are explained. Recent HSGT feasibility studies are reviewed and several potential implementation scenarios are discussed.

An implementation cost model is developed to evaluate particular HSGT systems in competition for implementation in specific corridors. Applications of the cost model are performed on both high speed MAGLEV and rail scenarios to determine major cost components for each technology type. In addition, a sensitivity analysis is performed using the two test case applications. The thesis concludes with suggestions for future research to identify methods and technologies capable of reducing guideway construction and maintenance cost through advanced guideway designs and automation of required guideway construction and maintenance procedures.

HIGH PERFORMANCE MAGLEV GUIDEWAY DESIGN
Ph.D. 2/93

This thesis demonstrates the influence of guideway design on overall high speed maglev system performance characteristics and suggests methods for improved, high performance maglev guideway design. The research focuses on three areas:

- advanced material design and application of a hybrid fiber reinforced plastic, FRP, non-magnetic concrete reinforcing rod
- hollow-box, narrow beam reinforced concrete guideway design and analysis, using both steel and hybrid FRP reinforcement
- dynamic beam analysis showing the interactions between beam length and frequency, and vehicle velocity and loading pad configuration

Structural requirements for a maglev guideway beam, including criteria for geometry, loads, deflections, durability, toughness, fatigues, and magnetic inertness, are defined and developed. Proposed construction methods are analyzed to determine the impact that the choice of method has on both the cost and structural design of the guideway. A conceptual design follows in which candidate cross-sectional shapes and materials are compared.

An investigation is made of the potential application of advanced plastic materials in the maglev guideway design. Specifically, a hybrid FRP rod is conceptualized, manufactured, and tested for potential application as concrete reinforcement in areas where non-magnetic reinforcement is required. A description is given of the hybrid FRP rod concept along with design procedure indicate expected beam lengths, widths, height, weights, frequencies, and costs for a number of vehicle load and deflection criteria scenarios. These sensitivity analyses indicate the importance of vehicle design on overall guideway performance.

Dynamic beam analysis is performed using both a finite element discretization and a closed form mathematical solution for simple beam spans having no assumed damping and, with uniform cross-section and stiffness properties. This closed form beam behavior solution is solved for convergent velocity cases, i.e., velocities that produce no beam residual vibrations. Sensitivity analyses performed on a variety of vehicle loading configurations demonstrate the importance of vehicle loading configuration to overall guideway performance. Dynamic analyses are confined to modeling the force of the traveling vehicle. Also, linear elastic beam behavior is assumed.

(17) SANCHEZ, RONALD

Ph.D. 8/91
STRATEGIC FLEXIBILITY, REAL OPTIONS, AND PRODUCT-BASED STRATEGY

This thesis proposes and undertakes to provide a theoretical foundation for the notion that there exists an optimal strategic flexibility which a value-maximizing firm will seek to acquire when competing in product markets characterized by uncertainty about technological outcomes and market preferences.

A central proposition of this thesis is that a firm's strategic flexibility can be exhaustively defined by certain basic types of choices a firm can make and that these basic choices can be characterized as generic real options which can be valued analytically. An options theoretic framework is developed for valuing some critical choices which a firm might make in setting its strategy for developing and producing new products. This exercise leads to several strategies based on design modularity in components, on designing new products as platforms for change, and on engineering design regimes which allow a

potentially large number of new models to be leveraged from a common system design. The product design and engineering skills on which these product strategies are based are then asserted to e critical core competencies which a firm can use to generate valuable new product options and thereby to achieve significant competitive advantage in dynamic product markets.

When product markets are characterized by uncertain technological outcomes and market preferences, the strategic flexibility/real options framework developed in this thesis is suggested as a means of illuminating the economic value which can be created by a firm which possesses these core competencies in product design and engineering. This thesis concludes by relating the strategic flexibility/real options framework for firm strategy developed in this thesis to other theoretical frameworks for formulating competitive strategy currently being used in this field.

(18) SLAUGHTER, E. SARAH

SSMTP 6/87
A STRATEGY FOR TECHNOLOGY TRANSFER WITH AN EXAMPLE APPLICATION OF THE WATER RESOURCES INDUSTRY

This thesis proposes a way to plan and implement a technology transfer in any situation. For this purpose, it establishes the three transfer types of placement, adoption, and adaptation, distinguished by the degree of control the recipient may exercise over the development, application, and modification of the technology. The argument is that the choice between these types is defined by the nature of the technology, its originators, and the potential recipients.

The strategy consists of two stages. The first identifies the status of the elements that determine the choice of transfer type. The second state targets certain elements to increase the potential for a successful transfer.

The method is designed for use by any participant in the process. The strategy is applied in a particular situation, the attempt by a research group in the Technology and Policy Program at MT to transfer methods for management and operations control to the water resources industry.

Ph.D. 6/91
RAPID INNOVATION AND INTEGRATION OF COMPONENTS: COMPARISON OF USER AND MANUFACTURER INNOVATIONS THROUGH A STUDY OF RESIDENTIAL CONSTRUCTION

According to conventional wisdom, builders of residential housing almost never innovate. In a detailed field-based study of the residential construction industry, the thesis documents quite a different picture: builders rather than the manufacturers of products and materials are the developers of almost all of the innovations in a sample (n=34) researched in depth.

Through structured interviews with over 50 individuals in the industry, specific data was collected on a sample of 34 innovations relating to a single technology in residential construction, the stressed-skin panel. As background for this detailed analysis, a sample of 117 innovations was also collected that are permanently installed in a residential building.

Measurement and comparison of economic incentives operating on builders and manufacturers in this industry show how a pattern of builder innovation can make economic sense. Builders develop needs for innovations in the middle of construction work, and at that time the cost of delay is very high. They must also integrate varied components into a whole operational residential structure. Under these conditions

builders find innovation to be cost-effective; as a result, they rapidly innovate. The prevalence of these innovations indicates a factory design partnership between these builder-users and manufacturers.

(19) TAYLOR, HENRY F. III

SMCE 2/92
SOLID WASTE MANAGEMENT: DECISION AND MARKET DILEMMAS

The municipal solid waste industry is changing, but neither government, industry, nor society is currently able to shape it to be efficient and productive in a way that everyone agrees in principle is right. The process that germinated during the last two decades when citizens and regulators began to question human impacts on the natural ecosystem, has grown into controversy and plunged the municipal solid waste industry into flux. At the same time, the choices for management methods have also grown, making consensus building more difficult for decision makers. This has led to cost increases, inefficient practices, and inequitable outcomes. Furthermore, market structure tends to discourage truly efficient outcomes even when satisfactory decisions can be made.

The majority of the issues affecting municipal solid waste management relate to one of two basic topics: market problems and decision making problems. A variety of issues make up each topic, and most current waste problems belong to one category or the other.

The public is directly responsible for solid waste generation, but capable of and willing to deny implementation of available technical solutions to it. Therefore, public perceptions about waste management, which have given society an irreconcilable view of the current solid waste management system, are responsible for some of the waste management problems. Generation continues to increase but public opposition (often characterized by the NIMBY syndrome) to every type of solution also rises.

Citizen and environmental groups have recently argued for implementation of more upstream waste management techniques, to gain the diffused societal benefits from more efficient material management practices. Their case, supported by sustainability arguments, demands that decision makers explicitly include the welfare of the environment in the decision making process. However appealing the case is, its implementation depends on subjective assessments of environmental attributes that are not only difficult to evaluate, but impossible to substantiate.

The problem of decision making is more pressing because landfills are closing due to new, stringent regulations, while new facilities have not kept pace replacing them. As closures have affected more areas, the price of waste management has risen, and added political heat to the problem. The uncertainties associated with the recent addition of waste minimization, as a policy goal for government, and "new" waste management technologies (such as recycling and composting), serve only to further confuse the issues.

Two different markets are impacted by the waste management field: the market for waste management services and the market for recovered materials. The waste management service market is dominated by large waste haulers whose market power stems from the nature of the business and is significantly influenced by the public sector. The market for recovered materials is young, and experiencing growing pains in many areas.

In the market for waste management services, waste haulers have monopoly power, while many of their household customers are not directly sensitive to the prices they charge due to the method communities typically use to raise waste management revenue. These both provide compound disincentives for efficiency gains in the public interest.

The secondary material markets have been flooded by recovered materials resulting from the implementation of recyling in many communities. These markets are a prerequisite for the movement to upstream management practices, and the case for efficient materials use depends on the existence of well-functioning materials markets. However, municipalities continue to pass recycling legislation without adequately addressing real market deficiencies.

There are no easy answers to these problems. Until technology advances produce goods and services that never make wastes, refuse will continue to build the largest monuments to mankind. Society can find enduring solutions only through the cooperation of the public, industry, and the government. If we, as a society, are to make and then implement good decisions that acknowledge equity and other cherished values, and employ the distributed, incentive based efficiences of the free market, we must learn new ways to explore all the issues, resolve the conflicts, and implement the best decisions for all those concerned.

Improving the solid waste management system is not costless, but it is not benefitless either. Unfortunately, we will never have an efficient, equitable, implementable waste management system until engineers stop presenting it as a technical problem, lawyers stop presenting it as a legal problem, economists stop presenting it as an economic problem; and environmentalists stop presenting it as an environmental problem. It's all of these. If all of these groups work together to examine the real tradeoffs involved in decision making and implementation, then we will make real progress in managing solid waste.

Ph.D.(Expected 5/95)
MODELING THE DYNAMIC TRANSITION IN SOLID WASTE MANAGEMENT

There have been remarkable changes in the solid waste management system in the US during the last decade. These changes have made current system of capacity management obsolete. A new system is needed. In several other markets, the same types of changes have already occurred. In these markets, state and federal agencies were created to oversee and manage the industry. The electric power and telecommunications industries provide good examples. In general, these services, like the solid waste management service, were also once locally owned, operated, and administered services. However, as technology and society changed, and the firms became more scale sensitive, there was a transition from local control to facility control in the market. Firms began to develop and exercise market power. Then, a need arose for better systems of market.management.In the solid waste management industry similar changes are occurring but there has yet to be a concerted effort on the part of the states or the federal government to implement any programs designed to manage the dramatically different industry that is developing. Many changes are occurring that lead to this conclusion. For instance, the number of locally controlled sources of waste capacity has been decreasing substantially during the last decade. This trend is expected to continue for the foreseeable future. This decrease in local sources of capacity has caused regionalization changes to occur where localities can no longer affect changes in many waste management policies or practices. Also, it is now evident that no entity, public or private, is currently in control of (or even charged with) management of the solid waste disposal capacity at this newly developed regional level. Common practices, such as requiring needs assessments before allowing developers to build new disposal capacity, only compound the evolving monopoly power of firms. While this strategy may be viewed as environmentally preferable, it may lead to guarantees of de-facto local monopolies for firms. To achieve this goal I will develop a regional waste management simulation system in four parts.

First, I will examine the historical context of the solid waste problem and characterize the resulting effects on the solid waste management system. Second, I will develop the

framework for my model, identify the appropriate variables, and map the causal system. I will determine the structural requirements which are necessary to accommodate the relevant governmental, market and social actions exhibited in the real solid waste management system. Third, I will build, test and calibrate the model. During construction, each subsystem will be initially built, calibrated, tested, and validated with appropriate data as separate a entity. Once all sectors are developed, they will be combined into a single model. Then, the final model will then be calibrated to a single historical case study in order to establish accuracy and validity using appropriate statistical tools. In the last (fourth) step of the thesis, the model will be used to examine prospective policy choices. I this case, different proposed policies will be analyzed in terms of the preferences of the waste management industry, public officials, and relevant non-governmental organizations.The primary expected result is the development of a model which can be used to assist in the formulation of thoughtful and robust solid waste management policies. There are three primary beneficiaries of the project. The government (broadly defined) will benefit from the project in at least three ways: policy makers will gain expert knowledge of the linkages in the municipal solid waste system that are clearly codified in terms of a numerical simulation model; policy makers will be able to experiment and learn about policy effects using a robust system; and decision makers will be able to use the system to develop cogent arguments, grounded in quantitative measures, for the use of specific policies to achieve specific ends. Waste management firms will benefit due to the effects of reduced uncertainty in the decision making system which is associated with a well-specified computer model of the solid waste management system. The public will benefit since better analysis will lead to more effective, more predictable (and quite possibly less expensive) waste management services.

(20) TONYAN, TIMOTHY D.

SMCE 2/88
AUTOMATION OF THE VISUAL INSPECTION OF CONSTRUCTED FACILITIES

This study has its first objective to identify where within the process of maintaining and inspecting constructed facilities automated vision technologies may be effectively applies. A second objective is to prove a conceptual framework of r how vision technologies with high potential can be applied in a facilities management system.

The study identifies that facilities management information requirements occur at three levels. These are the organizational level,the facilities level, and the component level. It is proposed that a computerized database arrangements system represents a potentially effective tool to assist in the operations, management, and inspection of constructed facility inventories of all types. The new concept forwarded in this thesis is the incorporation or a visual component into the facilities database.

An automated imaging system is proposed to initialize and maintain this visual component. the imaging would be done at three levels of detail: aerial, ground based, and detailed interior. Automated image analysis is presents as a tool enabling the extraction of useful facility inventory and inspection information firm the three types of image. Experiments are described, demonstrating the potential of automated image analysis to extract features of interest form each of these image types. The new concept forwarded in this thesis is the incorporation of a visual components into the facilities database.

An automated imaging system is proposed to initialize and maintain this visual component. The imaging would be done at three level of detail: aerial, ground based, and detailed interior. Automated image analysis is present as a tool enabling the extraction of useful facility inventory and inspection information from the three types of images. Experiments are described, demonstrating the potential of automated image analysis to extract features of interest from each of these image types.

Ph.D. 2/90
MECHANICAL BEHAVIOR OF CEMENTITIOUS FOAMS

There is a strong trend in U.S. residential construction toward the use of building components fabricated off the site. Structural foam core building panels are a particularly innovative building component that are increasingly used in residential construction. Foam core structural panels offer a combination of structural and thermal efficiency, design flexibility and reduced on-site construction time.

This thesis investigates the use of promising new materials in the face and core of residential structural building panels. An analysis has been completed to determine which materials would function most effectively as face and core materials in a sandwich panel. The most promising core materials were found to be wood foams, cement foams and reinforced polyurethane foams.

Low density cementitious foams have been investigated in detail. With their high stiffness per unit cost, low thermal conductivity, good fire resistance and ease of processing, cementitious foams offer the potential of significant performance advantage relative to existing core materials.

Cement and cement composite foams have been produced in the laboratory at densities ranging from less than 10 pcf to 120 pcf. Mechanical properties for cement foams from 10 pcf to 120 pcf have been measured. The microstructure of cement foams without aggregate has been characterized and models describing their mechanical behavior have been developed.

The addition of lightweight spherical aggregates (pre-expanded EPS spheres) at high volume fractions into a cement foam matrix produces a highly efficient microstructure in the resulting cellular composite. A thin, fully density cement past coating forms around the spherical aggregate, with the interstitial space between the aggregate filled with cement foam matrix. This microstructure has been modelled by describing the cell walls of the composite foam as sandwich beams.

This microsandwich cell structure provides cementitious foams at densities of 10 -12 pcf with the mechanical properties required to function effectively as a core in residential sandwich panels. Further improvements in properties and reductions in density are shown to be possible, indicating that cement composite foams are a promising material for use in building panel cores.

(21) TOOLE, T. MICHAEL

SMCE 6/90
STRATEGIC ISSUES IN STRESSKIN FOAM PANELS IN RESIDENTIAL CONSTRUCTION

Prefabricated components are playing an important role in decreasing the costs and increasing the performance of single family housing. This thesis proposes that the performance costs, and present market share of a component is a result of the following factors:

- the underlying characteristics and economic structure of the industry,
- the technological and performance characteristics of the component's design,
- the technological, economic, and organizational characteristics of the production, marketing, and installation processes associated with the component.

These factors are examined in detail for the stresskin foam panel industry and, on a general level, for components in residential construction. The technological aspects of stresskin foam panels are examined using a framework for understanding prefabrication introduced in this thesis. The economic structure of the stresskin foam panel industry is analyzed using a framework developed by Michael E. Porter for conducting a structural analysis of an industry. The technological, economic and organizational aspects of the processes associated with the production and sales of stresskin foam panels are analyzed using Porter's framework for conducting a value chain analysis. Possible strategic actions by individual producers and the foam panel industry as a whole are discussed.

Ph.D. 5/94
TASK AND ENVIRONMENTAL UNCERTAINTY AND THE ADOPTION OF TECHNOLOGICAL INNOVATIONS BY HOME BUILDERS.

An empirical investigation into two research questions pertaining to the adoption of technological innovations by small and medium-sized home building firms was conducted by multiple regression analysis of data collected from interviewing over 100 home builders across the country.

How are home building firms that are more apt to adopt technological innovations before they are widely diffused different from those that are less apt to do so? The research showed that home builders who are more apt to adopt non-diffused innovations have superior information processing abilities related to building innovations. These builders were found to tap into more sources of information about new products from portions of their organizational environments than did non-adopters. Information processing significantly differentiates these builders from those who are less willing to adopt innovations that are not widely diffused because the uncertainty level of most building innovations is quite high due to the complexity of the home building task and the complexity of the organizational environment facing home builders. No significant relationships were found to exist between adoption behavior and either company size, number of years the company has been in business, or market segment served (i.e., average house price).

How are home building firms that are more apt to adopt high uncertainty technological innovations before they are widely diffused different from those that are more apt to adopt low uncertainty innovations before they are widely diffused? The data provided evidence that the two groups differ in the characteristics of the individuals involved in innovation-related activities. Propensity to adopt high uncertainty, non-diffused innovations is associated with having higher numbers of functions (e.g., top management, office administration, sales, design, site supervision) involved in making adoption decisions. Each function possesses intimate knowledge of one or more sectors of the environment and can therefore help to reduce the uncertainty of how well an innovation would fit with the firm's task process and environment. Propensity to adopt high uncertainty innovations is also associated with having at least one individual with a building trades background involved in innovation-related activities. These individuals likely apply their tacit knowledge about the construction process to reduce the uncertainty relating to how well an innovation will be assimilated into the existing task process.

Propensity to adopt low uncertainty, non-diffused innovations is associated with having at least one individual with an architectural or engineering background involved in innovation-related activities. These individuals apparently apply engineering principles to reduce the uncertainty of innovations related to physical performance, but cannot reduce the uncertainty of high uncertainty innovations related to market acceptance. Propensity to adopt low uncertainty innovations is also associated with having a more positive attitude about adoption of innovations and/or higher tolerance of uncertainty. This factor does not play a critical role in relatively early adoption of high uncertainty innovations apparently

because it is overwhelmed by the need for effective gathering and processing of information about innovations.

The results of this research suggest that, contrary to the prevailing opinion within the home building industry, builders' adoption of technological innovations substantially reflects factors within their control. However, contrary to widespread public perception, the majority of home builders are neither apathetic nor excessively conservative about new building technologies. The results also suggest that the construct of uncertainty deserves a more prominent position within organizational diffusion theory.

EXHIBIT L
GRADUATE SUBJECTS FOR CONSTRUCTION ENGINEERING AND MANAGEMENT

I. DECISION SCIENCES/QUANTITATIVE TECHNIQUES

1.00	Computers and Engineering Problem Solving
1.146	Engineering Systems Analysis
1.151	Probability & Statistics in Engineering
1.155	Engineering Risk-Benefit Analysis
1.731 & 1.732	Water Resource Systems I & II (Optimization & Uncertainty)
4.55	Building Economics: Project Life Cycle Analysis
15.011	Applied Microeconomics
15.012	Macro & International Economics
15.062	Decision Support Systems
15.065	Decision Analysis

II. MANAGEMENT

A. Construction Management

1.40	Project Management (Undergraduate)
*1.421	Productivity and Competitiveness in Construction
1.431	Structuring Construction Industry Organizations
**1.432	Project Control
1.44	Law in the Construction Industry
1.45	Construction Finance
1.46	Strategic Management of Design and Construction
**1.481	Research in Construction Engineering and Management
1.962	Project Execution in the Industrial Sector
1.964	Alternative Contracting Methods
*1.965	Strategic Information Systems in Architecture Engineering and Construction
11.431	Real Estate Finance & Investment

B. General Management

15.311	Managerial Behavior in Organizations
15.314	Organization Design
15.412	Financial Management
15.415	Finance Theory
15.516	Financial & Cost accounting
15.568	Management of Information Systems
15.664	Management of Human Resources
15.812	Marketing Management

III. CONSTRUCTION TECHNOLOGY

A. Process

*1.422	Management of Technology Innovation in Construction
**1.481	Research Seminar in Construction Engineering and Management

* Direct result of PACT Research Areas Emphasis
** Major Inputs from PACT Research Projects

Course Listing (Continued)

1.96x	Industry Case Studies o Geo construction o Hazardous Waste Management
**1.123	Knowledge-Based Systems for Engineering Problem Solving
*1.551	Computer Aided Engineering I
**1.552	Computer Aided Engineering II
15.351	Introduction to Management of Technological Innovation
15.564 & 15.565	Information Technology I & II

B. Building

1.413	Construction Technology and the Building Development Process
*1.544	Innovative Structural Technologies
**1.592	Mechanical Behavior of Construction Materials
1.96X	Engineering Wood Structures
1.96X	Industry Case Studies o Failures o Geo-Construction
4.441	Building Structural Systems
4.461	Building Simulation
4.471	Control of Space Conditioning Systems
4.52	Advanced Design for Building Systems & Structures

C. Civil Construction

**1.22	Transportation Infrastructure Systems
*1.242	Highway Design, Construction, Maintenance and Operations
1.366	Foundation and Geo-Technical Engineering
1.383	Underground Construction
1.96x	Industry Case Studies o Heavy Construction Projects o Geo-Construction

Part IV

INDUSTRIAL INTERACTION

Since its inception in 1982, CCRE has had as one of its mission, to forge closer ties with and develop a strong liaison with the construction industry. In this regard, the Center has chosen several mechanisms for enhancing this relationship with industry. Over the past several years the Center has conducted numerous seminars, lectures, conferences and workshops in which topics of interest and concern to the construction industry have been addressed. The CCRE Newsletter which is published three times a year publicizes these activities and those relating to the Center's educational program. In addition, the Center has sought the participation of industry by recruiting industry specialists to come to M.I.T. and teach courses relating to construction. Others have acted as thesis readers for the Center's graduate students at the Masters level. This mechanism has provided an excellent opportunity for the students to obtain first-hand knowledge on topics of interest to the construction industry. On several occasions, such interaction has actually led to employment opportunities for the students.

Construction Industry Affiliates Program

The Center also initiated a ***Construction Industry Affiliates Program*** in an effort to bring together people from industry, government and the academic community to work as partners in construction research, development and education. The Program's goal is to enhance construction productivity by fostering new directions and applications for university-based research and education. The Program provides members with access to the resources of the Center; its faculty; professional staff; students, and their research and educational activities. Activities undertaken under this Program include:

- Research Briefing Workshops
- Roundtables
- Individual Research Briefings
- On-site Consultations
- Information and Personnel Exchange

Membership in the Affiliates Program is open to all who share an interest in the future of construction: general and specialty contractors; engineering and architectural design firms; owner and client organizations; financial institutions, materials and equipment manufacturers; and labor and other organizations who play a role in the construction process. The cost of membership in the ***Construction Industry Affiliates Program*** is negotiated individually based upon company size and expected activity. Typically, this fee can range from a low of $1500 for a small firm to a high of $15,000 for the largest design or construction firm.

The Consortium on the Construction Industry and Global Environment

Concern for the quality of the environment in recent years has brought about fundamental and far-reaching changes in global construction markets. As firms, governments, and the public gain a better understanding of the scope and urgency of this concern, new ways to mitigate or avoid ecological damage will emerge and new markets will arise. These markets demand creative corporate strategies and more sophisticated management skills, novel technologies, and a new understanding of the environmental, social, legal, and economic contexts of industrial and construction activity. The recognition of these global markets and borders, provides new challenges and opportunities at the intersection of environment, industry, and construction.

In response to these new challenges and opportunities, the Center for Construction Research and Education at M.I.T. has formed a consortium for collaborative research on the implications of global environmental change on engineering construction. ***The Consortium on the Construction Industry and Global Environment*** provides a research atmosphere for defining and fostering a comprehensive understanding of critical issues, identifying opportunities for new markets, appraising emerging technologies, and assisting member firms in developing appropriate strategies for participating in this major market. Firms and organizations who share a concern for the global environment are invited to participate in the Consortium.

Attendant benefits of joining this Consortium are:

- Opportunity to participate in formulation of a comprehensive research agenda for the Consortium.
- Opportunity to send Visiting Researchers to participate in the work of the Consortium, encouraging technology transfer.
- The ability to facilitate the transfer of technology by undertaking joint research projects.
- Opportunity to build working relationships with faculty associated with the program.

Founding Member fees are $150,000 and Associate Member fees are $65,000.

Roundtables

Concerned with the crisis posed by our nation's crumbling infrastructure, the MIT Center for Construction Research and Education (along with Touche Ross & Co. and Prudential-Bache Security) sponsored a series of roundtable talks in New York, San Francisco and Boston, involving

leaders in construction, engineering, government, finance, education, and management. Numbering 75 in total, the group included the Mayor of Cincinnati, the Director of the Milwaukee Metropolitan Sewerage District, a Congressman from Pennsylvania, the Governors of Massachusetts and New Jersey, the Administration of the Federal Highway Administration, the editor of Engineering News-Record, the former chairman of Standard & Poor, the Secretaries of several Departments of Transportation, executives from leading engineering firms and construction companies such as Louis Berger International, URS Engineers, C.T. Main, Perini Corporation, Parsons Corporation, Guy F. Atkinson Co., C.E. Lummus, and Turner International. The results of these series of Roundtables are published in a report entitled "Infrastructure Crisis."

In October of 1986, the Center hosted a Roundtable Meeting with 12 construction industry leaders from around the country. The topic for the meeting, productivity and competitiveness in construction. The Roundtable meeting led to a deeper understanding of the potential of joint industry and academic efforts for addressing competitiveness and productivity problems. Issues discussed by participants included international competitiveness in construction, the changing nature of construction supply and demand, education in the industry, the importance of R&D in areas of new technology and the future of construction.

CCRE Special Seminars

The Center has organized seminar series with guest speakers from industry presenting their views on the challenges facing the industry as a result of the changing nature of construction demand. Below is a sampling of some of the Center's seminars held at M.I.T.

- Ray Barnhard, Federal Highway Administrator.
  Topic: The Federal Role in Infrastructure Redevelopment.

- Jack Kavanagh, President of Badger America, Inc.
  Topic: Serious impact of rapidly changing market conditions for engineering and construction market companies specializing in the engineering and construction of hydro-carbon-related projects.

- Dr. George Peterson, Director of the Public Finance Center of the Urban Institute
  Topic: Availability of capital resources for financing infrastructure reinvestment.

- Warren Pettingell, Senior Vice President of Perini International Corporation.
  Topic: Critical factors for successful project management in the international market.

- Russell Stearns, President of the American Society of Civil Engineers and Dr. Franklin Agardy, President of URS Engineers

Topic: The engineering view on the growing challenges in water resources infrastructure redevelopment needs, and the vital role of infrastructure facilities in overall economic productivity in various geographical regions of the U.S.

- Gabriel J. Tibor of the World Bank.
  Topic: The need for technology in infrastructure construction that is appropriate to the institutional and management environment in which the completed facilities will subsequently be operated.

- Bryant Zimmerman, Senior Vice President of Guy F. Atkinson Company and Chairman of the National Contractors Association.
  Topic: Identification of constraints that limit the growth of labor productivity on large scale industrial projects.

Construction Seminars Series

The Center has hosted seminars, including the following:

1984-1985

- **Construction Industry Cost Effective Project.**
  Over 45 participants, representing owners, contractors and fourteen New England academic institutions were treated to a series of presentations organized by the New England Construction Users Council.

- **Financial and Banking Aspects of Overseas Construction.**
  Speaker: Lode G Beckes, Vice President, European Construction and Engineering Banking Center, Citibank, N.A.

- **Making Quality Come First in Construction.**
  Speaker: Joe C. Applewhite, Senior Vice President, Robert C. McKee, Inc.

- **A Case Study in Rail Planning, Dart in the Big D.**
  Speaker: Andrew C. Lemer, Vice President, PRC Engineering

- **Effects of Advanced Computation and Automation Building Research, Practice and Education.**
  Speaker: Richard N. Wright, Director, Center for Building Technology, National Bureau of Standards and President, Council for International Building Research, Studies and Documentation.

- **The Military Construction Process**
  Speaker: RADM William M.Zobel, Former Chief of Naval Civil Engineers and Commander, Naval Engineering Command

- **Future Applications of CADD to Engineering and Architectural Design**
  Speaker: William R. Laubscher, President of Great Lakes Region, URS Architects & Engineers

1986

- **Design for Construction Automation.**
  Speaker: Alexander H. Slocum, Assistant Professor, Civil Engineering, M.I.T.

- **An Expert System for Analyzing Construction Risks.**
  Speaker: Leston Nay, Project Software and Development

- **Building High Technology Facilities.**
  Speaker: William L. Maini, Symmes Maini & McKee Associates, Inc.

- **What is an Intelligent Building?**
  Speaker: Norman Kurtz, Principal, Flack and Kurtz Construction Engineers

1989

- **Seminar on the Design and Construction of Building with High Technology Requirements.**
  Professor Robert Logcher, Civil Engineering Department, Professor David Marks, Head of Civil Engineering, and William Porter, Professor of Architecture led the seminar in which numerous guest speakers from the MIT community and elsewhere participated.

1991

- **Seminar on History and Activities of National Association of Home Builders (NAHB) projects.**
  Speaker: Dr. Stan Mendelsohn, Director of the Housing Futures Project at Ball State University.

Special Lectures

The Center holds two special lectures a year; one is The James A. Henderson Memorial Lecture which was established in honor of James A. Henderson, an M.I.T. alumnus and Senior vice President and a Director of the Guy F. Atkinson Company; and the second is The Richard L. Mullin Lecture which is made possible by funds from the architectural and engineering firm of Symmes, Maini & McKee Associates.

Speakers for **The James A. Henderson Memorial Lecture** have included:

- **Joseph Anderson**, Senior Vice President and Manager of special Projects, Bechtel Corporation spoke on Mega-Project Development.

- **Thomas J. Henderson,** Chairman and CEO of Guy F. Atkinson Company, Who addressed the need for alternative disput r esolution methods.

- **Robert J. Kiley,** Chairman of the New York City's Metropolitan Transportation Authority, who talked about a major program of reconstruction and rehabilitation of the New York transit system.

- **Lieutenant General E.R. Heiberg III,** Chief of Engineers of the U.S. Army Corps of Engineers. His topic was "Foundation of Defense: Construction for National Security

- **Dana Huestis,** President of the Associated General Contractors of America talked on competition in the bidding process and competition in the marketplace.

- **Robert W. Page,** Assistant Secretary of Defense (Civil Works) examined the current state of the American engineering and construction industry.

- **Richard Ravitch,** Chairman, Metropolitan Transit Authority, New York City. His talk was on The Capital Revitalization of a Regional Transportation System: A Case Study of the Metropolitan Transportation Authority.

- **Howard Stussman,** Editor-in-Chief, of Engineering News Record presented a talk on "Construction 2000 (Technology as a Road, Not a Destination).

Speakers for **The Richard L. Mullin Lecture** have included:

- **Gerald W. Blakeley,** former Chairman of Cabot, Cabot, and Forbes, addressed a variety of issues relating to the changing roles of engineering, design and construction and their impact on future industry needs.

- **Ezra Ehrenkrantz,** President of The Ehrenkrantz Group, spoke on the Economics of Building Design.

- **Professor T.Y. Lin,** President of T.Y. Lin International and a Professor at the University of California at Berkeley. His topic was "Pioneering Prestressed Concrete in the U.S.A.

- **Henry L. Michel,** Chairman, Parsons Brinckerhoff Inc. The topic was "Global Challenges for the Construction Industry"

- **Wendel R. Wendel,** President of Space Structures International Corporation who talked about a new subject "Aerospace Design" which had been started in the Architecture Department.

- **Derish M. Wolff**, Pressident and CEO, of Louis Berger International Inc., who spoke on "The Consulting Engineering Profession in the 21st Century."

Distinguished Speakers Lectures

- **George Seaden**, Director of the Institute for Research in Construction, National Research Council of Canada spoke at M.I.T. on March 8, 1989 on "The Role of a National Research Institute and its Impact on the Construction Industry."

- **Horacio C. Reggini** of the National Academy of Science of Argentina spoke at M.I.T. on October 11, 1990 on "Computational Geometry Representation for Automated Design."

- **James B. Hudak,** Partner in Charge of Public Sector Strategic Planning at Arthur Andersen and Company, delivered a talk on November 1, 1990 entitled "Multifunction Polis: Partnering for New Global Technopolis".

- **Masahiko Kunishima** of Tokyo University presented several lectures in November of 1990 on "Durability Design for Concrete Structures."

- **John I. Carlson, Jr.**, former President of the Carlson Group, and Head of the Massachusetts Division of Capital Planning and Operations, Commonwealth of Massachusetts, presented a lecture on November 29, 1990 on "Alternative Construction Delivery Methods."

Conferences/Symposia

- In April 1985 a Conference was held to celebrate the **120th Anniversary of the Civil Engineering Department.** Representing CCRE were: Louis Berger, President of Louis Berger International, Inc.; Dennis Fitzpatrick, President of Daniel O'Connell's Sons, Inc.; James Paddock, Acting Dean and C.E.O. of Arthur D. Little, Inc.; Dr. Kenneth R. Maser, Research Associate of CCRE; and Robert Logcher, Professor of Civil Engineering, M.I.T.

- March 22, 1989. **A Symposium on Construction in the High-Tech Era**, co-sponsored by the Industrial Liaison Program and the Civil Engineering Department, CCRE, was held. Topics discussed included: "The Construction Industry - A Major Market for Innovative Materials, Products, and Ideas" and "Construction and the Materials Industry".

- October 18, 1989. **A Conference on Information Technology in Construction.** Over 70 participants from industry and academia met at M.I.T. for an Industry Forum for the Engineering and Construction Industry sponsored by the World Economic Forum.

- October 21-22, 1991. **A Symposium on Global Environment and the Construction Industry**, sponsored by Hazama Corporation and CCRE was held at M.I.T. Over 200 participants attended to hear the view and concerns of leaders from academia, government, and industry on environmental issues and how they affect the construction industry.

- May 12-13, 1992. **The Construction Inusry in the Northeast: Opportunities for the 21st Century.** This symposium was presented to commemorate the Tenth Anniversary of the Center for Construction Research and Education and was attended by over 200 construction industry executives, government officials, and academia leaders. The speakers addressed the broad range of technological, management, and market trends that are shaping 21st Century Construction.

- December 1992. **An Overview of the Construction Industry in the Global Environmental Era.** This symposia was presented in Tokyo to brief Japanese Construction industry executives and owners on the emerging opportunities in the environmental market.

- September 9-12, 1993. **The 1993 Industry Summit.** The Center organized and conducted a highly successful engineering and construction sector program which brought together over 100 industry executives from throughout the world.

- November 6-8, 1994. **Global Infrastructur1e Development.** In collaboration with the Global Infrastructure Fund Research Foundation Japan, MIT hosted symposium which addressed the topic of the role of investment in infrastructure as a fundamental prerequisite for sustainable development and for maintaining economic vitality and improving the qualty of the natural environment.

Courses Taught by Industry Leaders

As part of CCRE's commitment to encouraging construction industry involvement in both the research and education efforts at the Center, several firms have presented special courses over the years. They include:

- Camp Dresser & McKee, Inc.
  Hazardous Waste Management: Professional Approaches and Case Studies

- The Badger Company
  Project Management In Oil and Refinery Construction
  Project Execution in the Industrial Sector: A Case Study

- Beacon Construction Company, Inc.
  Structuring Construction Industry Organizations
  Construction Technology and the Building Development Process

- John I. Carlson, Jr., Former Head of the Massachusetts Division of Capital Planning and Operations
  Project Delivery in the Public Sector: Changing Times.

- Fletcher School of Law and Diplomacy, Tufts University
  Construction Finance

- Gadsby and Hannah
  Law and the Construction Industry

- George Macomber Construction Co.
  Case Studies In Strategic Management In the Design and Construction Value Chain

- Haley & Aldrich, Inc.
  Geo-Construction: The Geotechnical Environmental Aspects of Foundation a nd Earthwork Construction.

- Parsons, Brinckerhoff, Quade and Douglas
  Case Studies In Heavy Construction

- Pedrelli Development Company and The Carey Group, Inc.
  Construction Technology and the Building Development Process

- Simpson Gumpertz & Heger, Inc.
  Failures: A Perspective for Assessing the Design and Construction Process

Interviews with Industry Leaders

The Center has undertaken to solicit and publish the views and opinions of leading leaders from various segments of the construction industry on timely topics to the industry, and below is a sampling of those interviews:

- **James M. Becker,** President of Beacon Construction Company
- **Harold K. Forsen,** Senior Vice President of Bechtel Corporation
- **John F. Kennedy,** President of Kennedy & Rossi, Inc.
- **Ira Leighton,** Chief, Connecticut Waste Management Branch, EPA
- **Paul Levy,** Executive Director, Massachusetts Water Resources Authority
- **William L. Maini,** Chairman, Symmes, Maini & McKee Associates
- **Robert W. Page,** Assistant Secretary of the Army (Civil Works)
- **Dennis A. Fitzpatrick,** President of Daniel O'Connell's Sons, Inc.
- **David B. Perini,** President of Perini Corporation

Research Programs with DOD Laboratories, Government Agencies and Industry

- **Construction Engineering Research Laboratory (CERL):** Under a joint agreement CERL funded basic research at the Center by allowing the individual researchers to define interests and set up the research agenda on a task order basis. Examples: Construction Project Scheduling; Resource Constraint Scheduling, Leak Detector for a Subsurface Pipe System, Inland Waterway Repair, Condition Assessment of Lock Gates, Sandwich Panel with Foam Cores, Geographic Information Systems, and A Hazardous Waste Probe. Total award to M.I.T. was $600,000 over a three to four year period.

- **The Massachusetts Department of Public Works (MDPW)** awarded a project to refine the Commonwealth's system of highway maintenance and management and to introduce to the system new analytic and computer-based techniques. This was funded for two years at $200,000.

- **Innovative Housing Construction Technology**. A university-industry partnership to explore uses of new and advanced materials in the construction industry was formed at M.I.T. Building materials suppliers with a special interest in new housing construction materials and systems helped to support M.I.T. research into structural sandwich panels. Among the corporate sponsors of the research program were: Weyerhaeuser, USG, General Electric Plastics Division, and Mobay Chemical. The award was for $37,500 each year for two years.

- **New England Transportation Consortium** was formed to address transportation needs and problems common to the New England area. The agenda is set by its participants: Maine, Massachuetts, New Hampshire, Rhode Island and Vermont. Work has been on-going in the following areas: Truck Permit Projects; Bridge Deck Projects; Building Highways in Wetland; Bridge Railing Design; Development of Regional Workshops; Regional Training Programs and Impact of Heavy Loads. This program was awarded $400,000 a year for a four year period.

- **University Transportation Centers Program (UTC).** M.I.T. was designated one of ten universities to take the lead in establishing a four-year $40 million grants-matching program for the U.S. Department of Transportation. This program is intended to provide a national resource for research and training in both passenger and freight transportation. Examples of projects under this program are: Prediction and Measurement of Corrosion-Induced Cracking in Reinforced Concrete; Structural Applications of Polymer Composites in Transportation Facilities; Design of Concrete Bridge Decks with Isotropic Reinforcement; and Use of Information Technology for Improving Traffic Flows.

- **Intelligent Data Base and Design System** was awarded to M.I.T. by NTT of Japan at $1 Million per year for two years. The objective of this program has been to examine how computer-based technologies can be employed to improve consideration of various perspectives during the design process. The effort has focused on two physical systems: steel framed structural systems and mechanical piping systems.

- **Enhancement of Analytical Tools and Precision Design for Scissor-Link Deployable Structures.** This project was sponsored by the National Science Foundation for two years with $148,958 from NSF and $21,969 from the Natick Research Lab. The purpose of these two research projects were to investigate the feasibility of a new concept for not merely temporary shelters, but also for a whole array of deployable-collapsible relocatable structures.

- **Consortium on the Construction Industry and Global Environment.** This Consortium is funded at a level of $150,000 per year per member. The Consortium was formed to provide a research atmosphere for defining and fostering a comprehensive understanding of critical issues, identifying opportunities for new markets, appraising emerging technologies, and assisting member firms in developing appropriate strategies for participating in this major market.

- **Reconstruction of Disaster Areas.** Efforts have been undertaken to provide assistance to disaster areas by focusing research in reconstruction and development of educational support systems. This program was funded over a five year period at $400,000 per year.